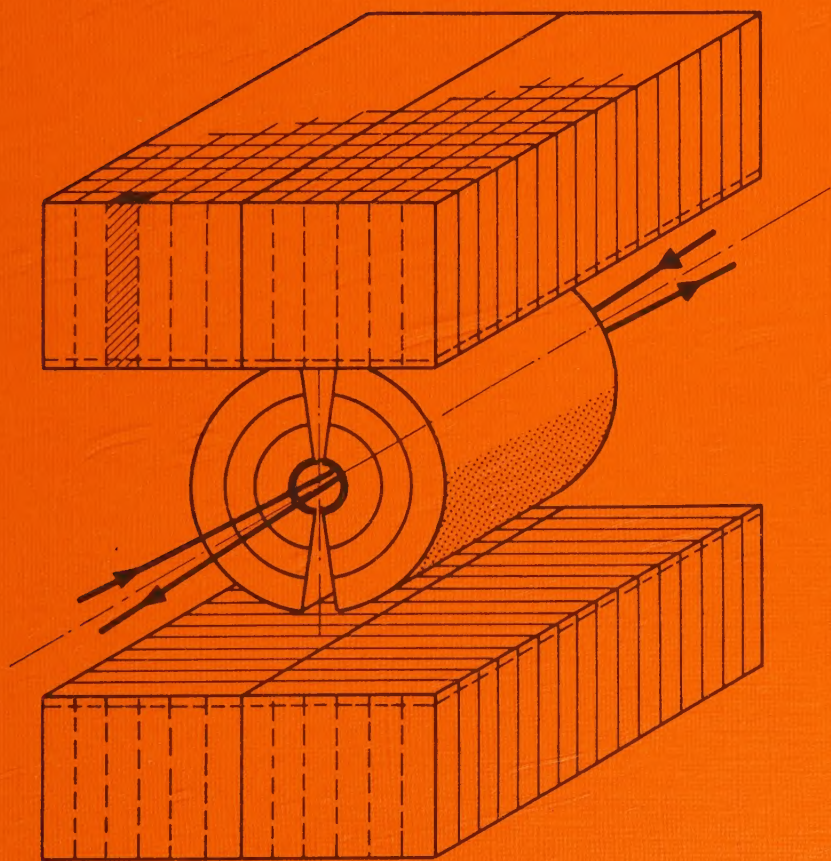


A STUDY OF PP AND $\bar{P}P$ INTERACTIONS AT THE CERN INTERSECTING STORAGE RINGS

Torsten Åkesson



LUND 1983

A STUDY OF PP AND $\overline{P}P$ INTERACTIONS AT THE CERN
INTERSECTING STORAGE RINGS

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by

Torsten ÅKESSON
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Title and subtitle A study of pp and $p\bar{p}$ interactions at the CERN Intersecting Storage Rings.		
Abstract This thesis consists of five parts: 1. A calculation of the <u>Transverse Energy Spectra</u> in 25 and 60 GeV pp collisions and 540 GeV $p\bar{p}$ collisions. The <u>jet fraction</u> is found to be sensitive to the detector acceptance. 2. A measurement of the <u>jet cross section</u> at 45 GeV pp collisions. The cross section is compared with measurements at 63 GeV and 540 GeV. The <u>jetproduction</u> is found to be consistent with a QCD Monte Carlo model. 3. A comparison between $p\bar{p}$ and pp interactions at $\sqrt{s}=53$ GeV. Differences observed can be contributed to quantum number changes in the initial state. No effects of strong annihilation is observed. 4. A report on the construction and performance of an <u>imaging drift chamber</u> at the <u>Axial Field Spectrometer</u>. The chamber is found to work well in the surroundings of a high luminosity machine. 5. A test measurement on a <u>dE/dx detector</u> using Flash ADC's.		
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A STUDY OF PP AND $\bar{P}P$ INTERACTIONS AT
THE CERN INTERSECTING STORAGE RINGS.

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LUND 1983



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A thesis in High Energy Physics based on the
following five papers:

- I : T.Åkesson, H-U.Bengtsson, Transverse energy distribution and
hard constituent scattering.
To be published in Physics Letters B
- II : T.Åkesson et al., The jet cross section in pp
interactions at $\sqrt{s} = 45$ GeV and
its $\sqrt{s}$ dependence.
CERN/EP 8301 submitted to Physics Letters B
- III : T.Åkesson et al., A comparison between $\bar{p}p$ and $p\bar{p}$ interactions
in the central region at $\sqrt{s} = 53$ GeV.
Physics Letters 108B(1982)
- IV : D.Cockerill et al., Performance of the AFS vertex detector at
the CERN ISR
Physics Scripta Vol.23(1981)
- Appendix : A Maximum Likelihood method for dE/dx analysis (R807/229)
- V : T.Ludlam et al., Particle identification with a fine sampling
ionization loss detector.
Proc. International Conference on Instrumentation
for Colliding Beam Physics.
SLAC, Stanford, California, February 1982

During my time as Graduate Student in the High Energy
Physics group at University of Lund, I have become coauthor
in a large number of publications. For this thesis I have
only **selected** publications where I have made a major
contribution

INTRODUCTION

Particle physics has become remarkably simple during the last two decades. From a world with a large number of "elementary particles" interacting in a complicated manner with each other, the picture has changed to a world with a small number of pointlike particles (quarks and leptons), interacting in a simple way, described by field theories obeying the principle of local gauge invariance.

An important step to this picture was the study of Deep Inelastic Scattering, proposed by ref.1, and later measured(2) at Stanford Linear Accelerator Centre, in electron proton collisions. Deep Inelastic Scattering means that leptons making very inelastic collisions with hadrons, are scattered as if they have made elastic collisions with objects much smaller than the hadron. This in turn proves that the hadron itself is made out of smaller objects(partons,quarks). This is of course in complete analogy with the discovery by Rutherford, of the atomic nucleus, when he radiated a gold foil with alpha particles.

The result from Deep Inelastic Scattering leads to new predictions(3): The transverse momentum (p_T) distribution of the produced particles in inelastic hadronic collisions should deviate from an exponential falloff (e^{-ap_T}), to a more gentle $f(x_T)p_T^{-n}$ ($x_T=2p_T/\sqrt{s}$) slope at high enough p_T because of pointlike parton-parton scattering. This was soon verified by experiments(4), and high p_T physics was born.

The physical picture is that the high p_T particles are contained in a jet of particles from the fragmentation of the scattered hadron constituents. As a consequence, the particle density should be higher close to the high p_T particle, and opposite to it, than perpendicular to it's direction. Experiments with high p_T single particle triggers(5) observed this, but there was some uncertainties: the enhanced particle density close to the trigger particle could maybe be explained by resonance production, and the enhancement opposite to the trigger would also be expected from momentum conservation.

The answer to this uncertainty is called calorimeter. The first calorimeter experiments(6) at FNAL measured a "jet cross section" several hundreds of times larger than the single particle cross

section. The calorimeters in these experiments had about the same size (1.5 sr) as the expected jet size, hence the experiments could not so clearly see if the particles in their high p_T events ($0.5 < p_T < 7.0$ GeV/c), preferred to come in collimated particle showers. This could be examined in the next generation of fixed target calorimeter triggered experiments(7), and one got two surprises:

- i) The "jet cross section" for a calorimeter covering 1.6 units of rapidity and the full azimuth, is about five orders of magnitude larger than the single particle cross section.
- ii) There was no sign of any collimated particle showers; one found only high multiplicity isotropic events, ie one wasn't measuring the jet cross section at all.

This lead to a lot of speculation on the existence of jets in hadronic collisions.

JET PHYSICS

The first paper(I) in this thesis gives an explanation to why these experiments did not see any constituent scattering, and predicts that jets should emerge at higher center of mass energies. We are making the same arguments on the transverse energy spectra as is made on the single particle spectra in (3). In our paper the E_T spectra is treated as being composed of two components: one given by an uncorrelated convolution of multiplicity and p_T distributions, and the other given by a constituent scattering model(16). This paper was first presented at the XXI conference in High Energy Physics in Paris 1982. At the same conference two experiments reported the observation of jets in hadronic collisions. One experiment(8) was the Axial Field Spectrometer (AFS) at the ISR, and the other(9) was the UA2 at the $\bar{p}p$ collider.

The second paper(II) in this thesis presents a measurement of the inclusive jet cross section at $\sqrt{s} = 45$ GeV and compares it with the cross section at $\sqrt{s} = 63$ GeV, measured by the same experiment(8), and with the cross section at 540 GeV $\bar{p}p$ collisions from the UA2 experiment(9). The comparison between the two ISR measurements is made with a QCD motivated Monte Carlo model(10).

The result agree in slope, normalization and energy dependence with the theoretical prediction. In analogy with the single particle cross section and the idea of scaling, the inclusive jet cross sections are fitted to a function factorized into a part only dependent on a dimensionless parameter, and to an effective p_T slope. A fit including the collider experiment(9) gives roughly the same effective slope as a fit including the ISR measurements only. The three different measurements are summerized on the last figure of paper II, together with measurements of the single particle distribution(13). The effective slope has been divided out, so the figure shows the x_T dependence only, and it is interesting to note that the slope for the single particle measurements is the same as for the jet measurements at high x_T . This can be interpreted as that the x_T dependence describes the convolution of the proton constituent structure function. The same figure shows a difference between the two experiments: AFS measures at high x_T and the UA2 measures at low x_T . ISR is consequently mainly a quark-quark and quark-gluon collider while UA2 measures gluon-gluon collisions. This is a consequence of the higher luminosity at the ISR, and that the cross section falls with an effective slope at fixed x_T . Fig.1 shows roughly where in x_T the two experiments are sampling the structure functions (parametrized by (14)).

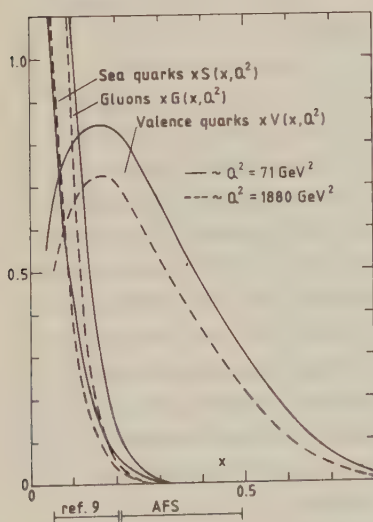


Figure 1 : Parton distributions parametrized by Buras & Gaemers(14). It is indicated in the figure where UA2(9) and AFS are sampling the structure functions.

The new era of jet physics using calorimeters at hadron colliders, will make it possible to study the strong interaction in reactions where the initial state particles (quarks and gluons) are coloured. I believe that this type of reactions will give a lot of information on the dynamics of strong interaction. It is here that the complete process (on the Feynman diagram level) can be calculated with perturbative QCD, and the non calculable processes (the fragmentation) is bypassed by measuring on the whole jet.

A COMPARISON BETWEEN $\bar{p}p$ AND pp INTERACTIONS

The third paper(III) presents a comparison between $\bar{p}p$ and pp collisions at $\sqrt{s} = 53$ GeV. This comparison was made when antiprotons was injected into the ISR for the first time. The antiprotons in the ISR gives four times higher center of mass energy than what was previously used for this type of collisions. The aim for this comparison was to look for effects from strong annihilation, quantum number effects from the fact that one of the incoming beams is made of antiparticles, and finally to see if something unexpected happens in this new energy region for $\bar{p}p$ collisions.

Effects from quantum number conservation are clearly seen, like the difference in K^+/K^- ratio from the change in associated kaon-hyperon production. There is also a change in the distribution of the protons and antiprotons coming into the central region. The ratio of produced protons and antiprotons in $\bar{p}p$ and pp collisions as a function of rapidity, raises an old question on the effect of braking protons(11). It is clear that protons and antiprotons from the beams get pushed into the central region and even into the backward hemisphere. This can be seen from the rapidity ratio (fig.5 in the paper) which differs from one at $y=0$. In fig.2 the curves are drawn after measurements(4) to illustrate this effect. Unfortunately the event sample was not big enough to see if there is a correlation between stopping one of the beam particles and stopping both of them. To see such an effect would require at least one order of magnitude more integrated luminosity, since out acceptance for proton identification in the drift chamber, is limited to a small kinematic region ($0.2 < p_{lab} < 0.8$ GeV/c), and there the mean efficiency is about 50%.

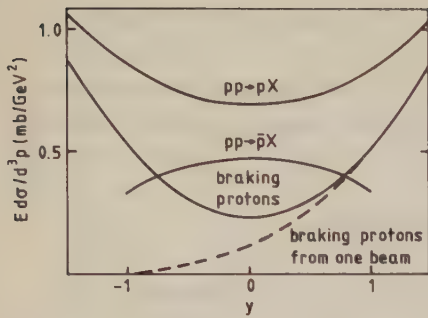


Figure 2 : Invariant cross section for the production of protons and anti-protons in pp-interactions measured by ref 4. The dashed line shows the effect of slowed down protons.

No evidence for strong annihilation was observed, neither in the kaon production nor in the multiplicity distribution, although there is an indication of an enhancement in the high multiplicity region in the ratio of the two multiplicity distributions.

For the future of $\bar{p}p$ physics at the ISR, the luminosity is crucial. From the first results, there has been no sign of a big (non trivial) difference between $\bar{p}p$ and pp inelastic collisions, so we have to go to more rare final states to study the effect of strong annihilation.

THE CENTRAL DRIFT CHAMBER AT THE AFS

The fourth paper(IV) describes the construction and performance of the imaging drift chamber, surrounding the interaction region in the Axial Field Spectrometer. This instrument was used for selecting good events by a vertex requirement in the second paper(II), and was the main equipment for the analysis in the third paper(III). The drift chamber is optimized for the high event rates at a hadron collider like the ISR (up to 2 MHz), which means that the maximum allowed drift distance must be significantly smaller than for a similar detector(12) at an electron machine. The chamber get the track coordinates in space directly, since it uses charge division for the coordinate perpendicular to the magnetic field. This together with the large point density

along the track, makes the efficiency in pattern recognition very high. The large number of points along the track makes it also possible to identify particles by dE/dx . This identification method worked very well and in an appendix a Maximum Likelihood method for dE/dx analysis is described.

A TEST BEAM MEASUREMENT ON dE/dx IDENTIFICATION

The last paper(V) describes an effort to achieve dE/dx identification in the relativistic region, with the help of a new ionization sampling technique. In previous detectors using dE/dx identification, the sampling has been done using a large number of anode wires each giving one measurement. This new method gives several measurements per wire using Flash ADC's to sample the ionization. The first measurement(15) using this technique, showed a significant improvement in the resolution when the sample size was reduced to smaller than a few mm. That measurement used only one readout wire. This paper describes an extension of these measurements to a chamber with a more realistic number of channels and longer drift distance. The result is similar to (15), but there is room for improvements in the pulse shaping, which complicated the offline analysis and limited the accuracy of the measurements.

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Transverse Energy Distribution
And Hard Constituent Scattering
in Hadronic Collisions

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ABSTRACT: We estimate the contributions to the total transverse energy spectrum from hard constituent scattering and the soft hadronic spectrum in hadron collisions. The transverse energy at which jet production starts to dominate is found to be essentially independent of the cms-energy (for large enough $\sqrt{s}$) and roughly a linear function of rapidity and azimuthal angle interval included. Calculations are presented for pp collisions at $\sqrt{s} = 25$ and 60 GeV, and $\bar{p}p$ interactions at $\sqrt{s} = 540$ GeV.

(Submitted to Physics Letters)

1. Introduction

Constituent scattering in hadron collisions has been studied for several years at the ISR, FNAL and the SPS. Most experiments have been conducted with a single particle trigger, i.e. the inclusive transverse momentum spectrum and the particles associated with a single high- p_T particle have been studied. One of the difficulties with these experiments is to estimate the trigger bias introduced by the requirement of a single high- p_T particle. To achieve an unbiased study of high- p_T reactions, experiments have been designed to trigger on the p_T -sum of all the particles in the event and to let Nature decide whether this p_T -sum is to be produced by a few high- p_T particles focused in jets or from a vast amount of low- p_T particles. A result from an experiment of this kind, NA(5) [6], shows that Nature prefers to create a large number of low- p_T particles. From this it has been inferred that to look at constituent scattering one has to study events with a single particle trigger, because using a calorimeter trigger just means triggering on multiplicity. This argument is obviously wrong since reducing the solid angle of the calorimeter to zero gives a single particle trigger, and increasing the solid angle by an increment ϵ will of course not immediately yield a multiplicity trigger. On the contrary, there has to exist a continuous relation between trigger acceptance, center-of-mass energy and fraction of triggers coming from hard constituent scattering. In this paper we examine that relation.

The approach we use is to consider the total transverse energy (ΣE_T) spectrum as built up from two parts: a soft contribution given by the multiplicity distribution and the exponential transverse mass distribution, and a hard contribution caused by constituent scattering. We then examine where in ΣE_T the constituent scattering mechanism starts to dominate for a given $\sqrt{s}$ and trigger acceptance.

2. The Soft Contribution

In the low- p_T region ($p_T < 1.0$ GeV/c) there seems to be no strong coupling between the p_T of a particle and the associated multiplicity [1]. In addition, there is no variation in the mean p_T with respect to the multiplicity. Therefore, it is tempting to calculate the soft part of the ΣE_T spectrum as it would have been done in the 60's, by folding together the multiplicity distribution and the transverse mass distribution as independent distributions to form a total transverse energy ($\Sigma E_T = \Sigma \sqrt{p_T^2 + m^2}$) distribution. This is in fact the method employed here.

We have used as a transverse mass distribution a fit from [2]:

$$f(\mu_T) = C_1 \cdot \mu_T \cdot e^{-7.145 \mu_T}$$

$$\int f(\mu_T) d\mu_T = 1$$
(1)

The ΣE_T distribution for a given multiplicity n is then given by $f(\mu_T)$ convoluted with itself n times:

$$h(\Sigma E_T[n]) = f * f * \dots * f(\Sigma E_T)$$

$n \text{ times}$

(2)

There has to be a cut-off for the lowest allowed transverse mass. In this analysis we have set $\mu_{T \text{ min}} = \text{Min}(\sqrt{p_T^2 + m^2}) = 0.2$ GeV.

For the multiplicity distribution we have used the one given by [3], which gives as result a spectrum that agrees quite well with the measurements from NA5:

$$P_n = (1 - \beta)^2 (n + 1) \beta^n$$

$$b = \frac{\langle n \rangle}{\langle n \rangle + 2}$$
(3)

This leads to the ΣE_T -distribution

$$\frac{1}{N} \frac{dN}{d\Sigma E_T} = \sum_{n=1}^{\infty} h(\Sigma E_T[n]) P_n \Theta(\Sigma E_T - n \cdot \mu_T \min) \quad (4)$$

This distribution is now calculated for pp collisions at $\sqrt{s} = 25$ and 60 GeV, where the particle density is taken to be 3/2 times the charged density measured by [4] (Streamer chamber). For $\sqrt{s} = 540$ GeV $\bar{p}p$ interactions, the same procedure is followed, taking the particle density from [5] (UA5).

3. The Jet Contribution

For the hard scattering part, we have used a Monte Carlo program including all α_s^2 -processes [7], based on the Lund Monte Carlo for soft hadronization. A full presentation of the physics underlying this program can be found in [8]; here, only a brief summary of the basic ingredients will be given.

The basic assumption behind the Lund model approach is that of the existence of two different time-scales. On the short time-scale, characterized by $1/\Lambda_{\text{QCD}} \sim 0.5$ fm, coloured objects are to all practical purposes free, and perturbative QCD is applicable. After scattering has occurred, however, the partons are connected by the colour force field, the breaking up of which is responsible for the eventual hadronization. In [9] it is shown how a given Feynman diagram can be associated with one or more colour flows, i.e. with specific final string configurations. The cross-sections corresponding to these different topological states are calculated in [8]. The program generates the string configurations according to their respective probabilities, and the Lund jet model is then used to fragment the strings. The theoretical ideas behind the hadronization model are expounded in [10]: in short, a string is always stretched from quark to antiquark (or diquark) via the gluon(s); the Monte Carlo implementation of this part is presented in [11].

Particles are considered to consist of valence quarks (antiquarks) and gluons only, each carrying a primordial k_T . The gluon is viewed as being emitted by a particular quark

(antiquark), which has to 'pay' for this by compensating for all of the primordial k_T of the gluon. This approach is used in order to avoid the introduction of further free parameters.

The jet contribution is generated using structure functions without explicit scale-breaking terms, and a constant α_s of 0.2.

4. Results

The results of our analysis are shown in figs.1-4. From figs.1-2 it is clearly seen how the soft contribution to the total transverse energy spectrum falls much faster than the jet contribution; after crossing over, the latter very quickly becomes the all important part. For the lowest energy, however, this cross-over will never occur at all, if the acceptance is too large (fig.1a). In fig.3 we have plotted $\Sigma E_T/\sqrt{s}$ for the intersection points as a function of azimuthal angle included in the trigger: the functional dependence is roughly linear. In fig.4 the same is done with the included rapidity interval on the ordinate: here, too, the dependence seems to be essentially linear. An estimate of the dependence on $\sqrt{s}$, which can be gathered from a comparison between a, b & c of figs.3 and 4, gives something like $\Sigma E_T(\text{cross-over}) \sim \sqrt{s}^{0.00-0.05}$, i.e. $\Sigma E_T(\text{cross-over})$ is essentially independent of $\sqrt{s}$ in this approach. The resulting formula for the total transverse energy where je production starts to dominate will then be:

$$\Sigma E_T(\text{cross-over}) \sim 12 \times \Delta y \times \frac{\Delta \phi}{360^\circ} \text{ (GeV)} \quad (5)$$

if Δy is the rapidity interval and $\Delta \phi$ the azimuthal angle interval included in the trigger. It can be noted, that according to this calculation NA5, where $\Delta y = 1.6$, will never see jets using the full calorimeter angle.

It should be pointed out that the soft part is rather sensitive to the tail of the multiplicity distribution: small changes at the edges, where statistics are poor, effect large corrections in the soft hadronic spectrum. In addition, short

range correlations will tend to make the ΣE_T -spectrum flatter. This will of course especially affect the spectrum for small trigger acceptances. For the hard part, the introduction of scale-breaking terms in the structure functions and the use of a running coupling constant would make this contribution fall more steeply. However, we do not think that this will seriously affect the functional dependence of ΣE_T (cross-over); it will increase the value of the constant appearing in the formula (5), though. We nonetheless think ourselves justified in concluding that finding jets in calorimeter experiments is not just a question of using high enough energy, but also, and much more so, of having a suitable acceptance. On the other hand, to see jets there is obviously no need to resort exclusively to single particle triggers.

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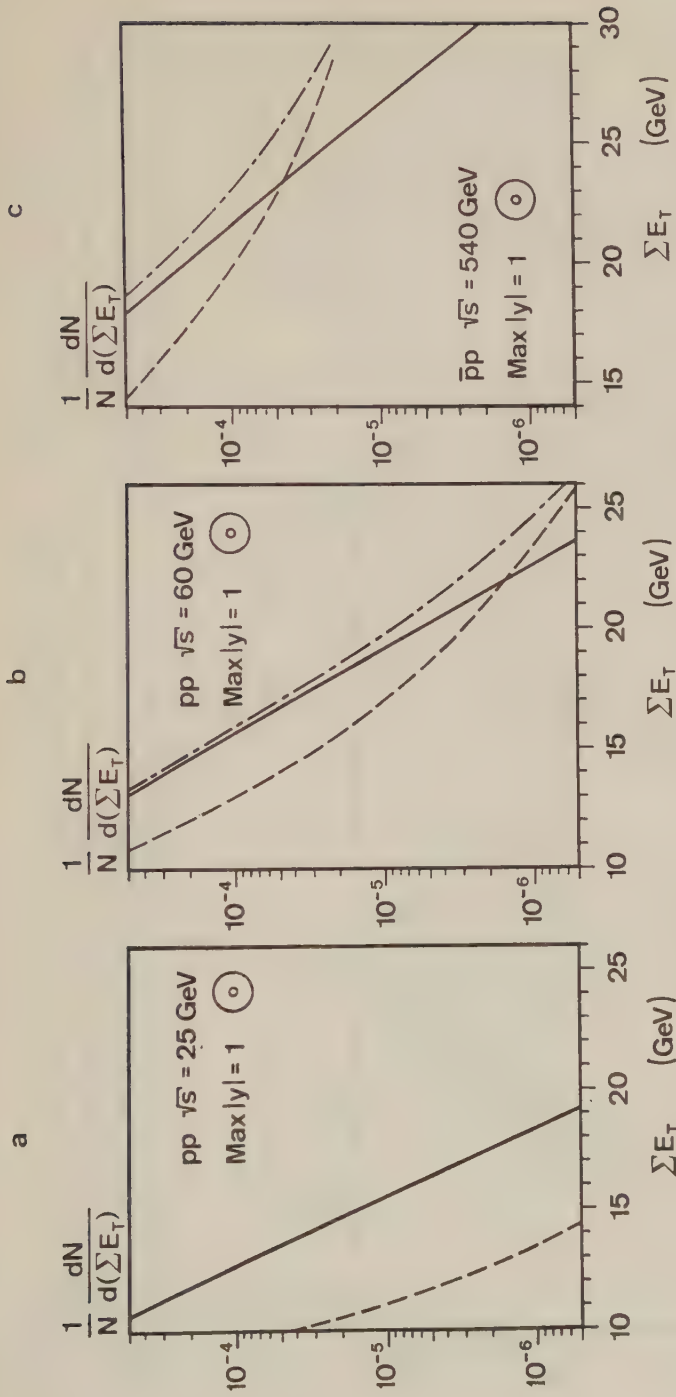


Fig.1 Contributions to the total transverse energy spectrum, $1/N \cdot dN/d(\Sigma E_T)$, from the soft hadronic spectrum (full line) and hard constituent scattering (dashed line). The sum is represented by the dash-dotted line. The plots are made including particles with rapidity between -1 and 1 and full azimuth (360°). (a) pp at $\sqrt{s} = 25$ GeV; (b) pp at $\sqrt{s} = 60$ GeV; (c) $\bar{p}p$ at $\sqrt{s} = 540$ GeV.

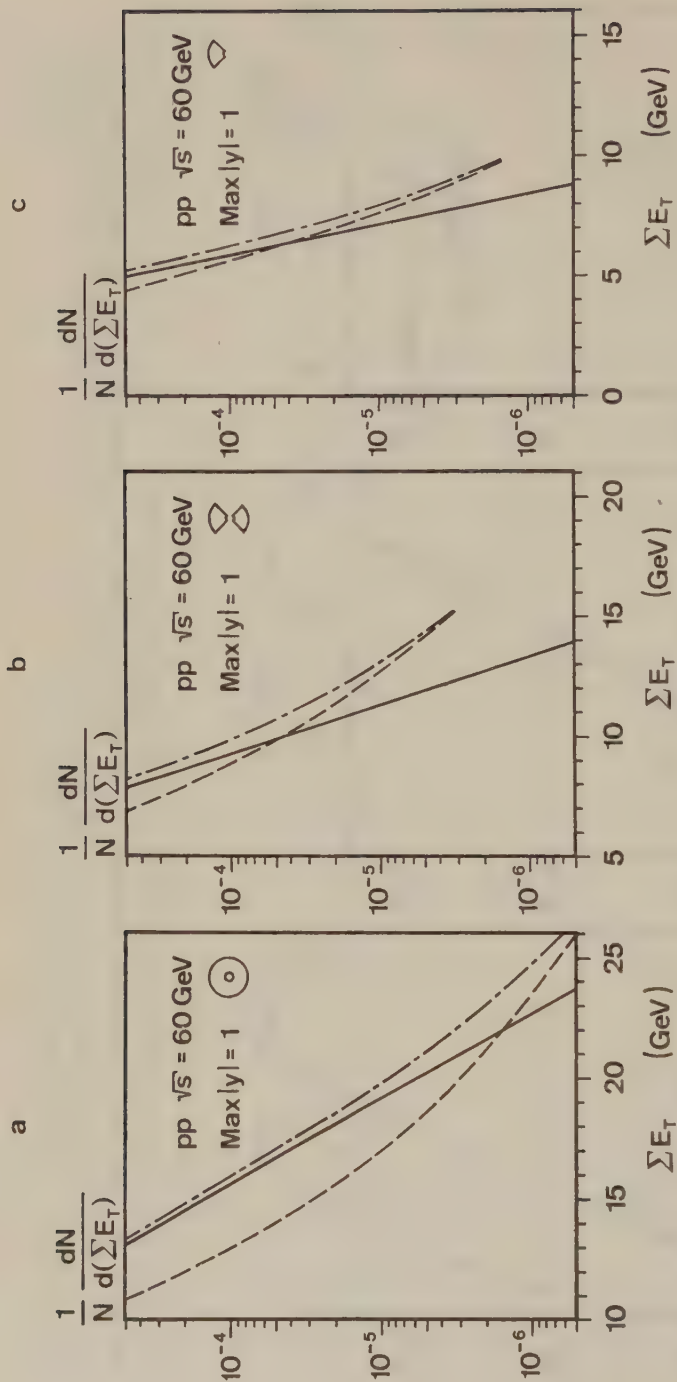


Fig.2 Contributions to the total transverse energy spectrum from the soft hadronic spectrum (full line) and hard constituent scattering (dashed line). The sum is represented by the dash-dotted line. The plots show pp at $\sqrt{s} = 60$ GeV and are made including particles with rapidity between -1 and 1 . (a) Full azimuth (360°) included; (b) one half of azimuth ($90^\circ + 90^\circ$) included; (c) one quarter of azimuth (90°) included.

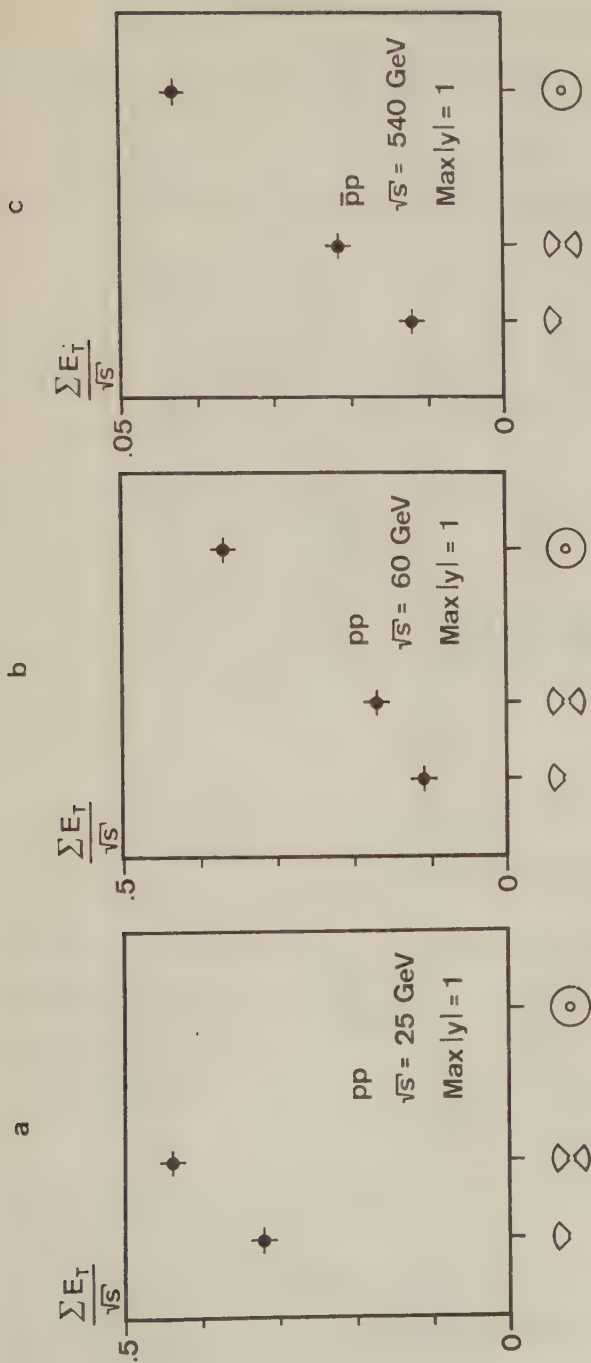


Fig. 3 $\Sigma E_T / \sqrt{s}$ for the intersection points between the soft and hard contributions as a function of azimuth included. Particles have rapidities between -1 and 1 . (a) pp at $\sqrt{s} = 25$ GeV; (b) pp at $\sqrt{s} = 60$ GeV; (c) $\bar{p}p$ at $\sqrt{s} = 540$ GeV.

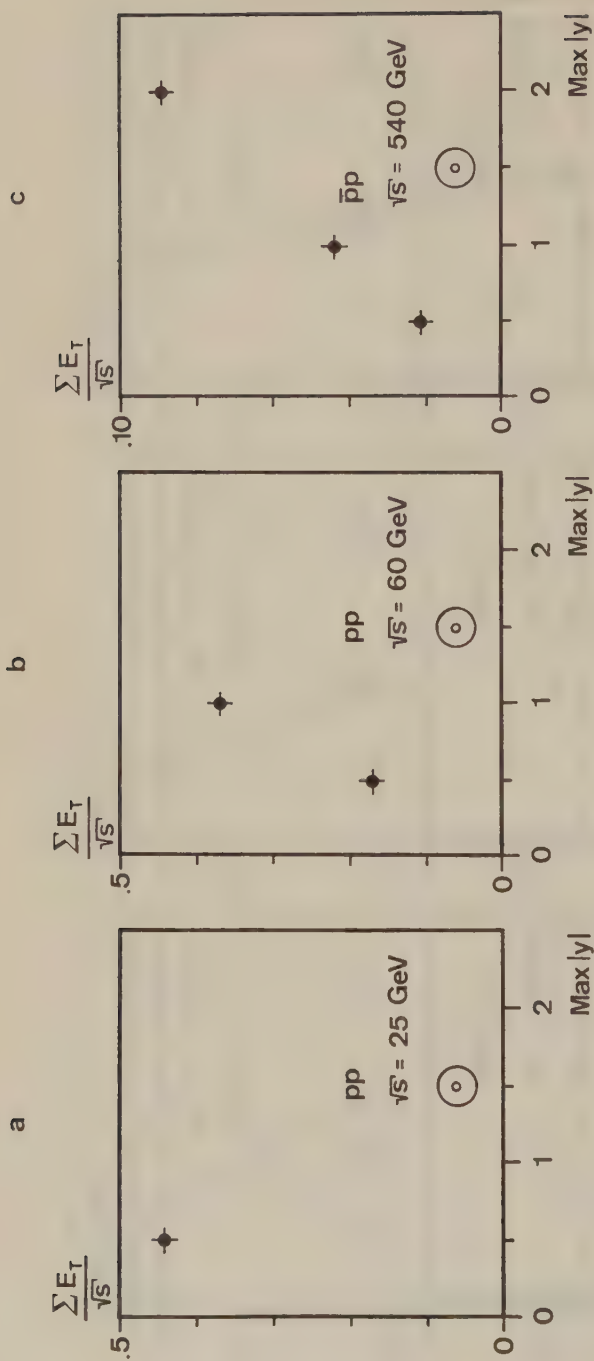


Fig. 4 $\Sigma E_T/\sqrt{s}$ for the intersection points as a function of rapidity interval included. The plots are made with full azimuth (360°) included. (a) pp at $\sqrt{s} = 25 \text{ GeV}$; (b) pp at $\sqrt{s} = 60 \text{ GeV}$; $\bar{p}p$ at $\sqrt{s} = 540 \text{ GeV}$.

THE JET CROSS-SECTION IN pp INTERACTIONS AT $\sqrt{s} = 45$ GeV AND ITS $\sqrt{s}$ DEPENDENCE

The Axial Field Spectrometer Collaboration

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ABSTRACT

The differential cross-section for production of jets in pp interactions at $y = 0$ and p_T from 6-12 GeV/c has been measured at $\sqrt{s} = 45$ GeV at the CERN Intersecting Storage Rings and compared with a previous measurement at $\sqrt{s} = 63$ GeV. The data were obtained using a 2.1 sr hadron calorimeter which was triggered on transverse energy. The energy dependence of the jet cross-sections is well described by $(1-x_T)^m \cdot p_T^{-n}$, with $m = 10.6 \pm 1.0$ and $n = 5.3 \pm 0.2$. The results are in good agreement with predictions obtained from a QCD-motivated model.

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Recent calorimeter-triggered experiments [1-3] at $\sqrt{s} = 63$ GeV and 540 GeV have observed an important contribution from jet production at sufficiently large transverse energy. Specifically, the final-state particles are found to be emitted in a solid angle significantly smaller than the acceptance of the triggering calorimeters. Such events are interpreted in terms of hard scattering of the hadron constituents, and provide a relatively unbiased way of studying deep-inelastic hadron-hadron scattering [4]. However, similar experiments at lower $\sqrt{s}$ [5] did not find jet production to be dominant, even at the highest accessible E_T . This can be explained in terms of contamination of the jets by beam fragmentation [6] and significant smearing of the hard scattering by gluon bremsstrahlung [7].

The energy ($\sqrt{s}$) dependence of the jet production cross-section is clearly of interest, and in this paper we report on measurements at $\sqrt{s} = 45$ GeV which complement our recent 63 GeV data [1,2]. The 45 GeV data were taken with the same apparatus and processed with the same off-line analysis chain as the 63 GeV data, which enables us to minimize the experimental systematic uncertainties. In addition, we relate our measurements to the jet cross-section from $p\bar{p}$ collisions at $\sqrt{s} = 540$ GeV.

The results were obtained using the Axial Field Spectrometer (AFS), which was triggered on large transverse energy E_T , deposited in a 2.1 sr uranium/copper scintillator calorimeter consisting of 192 towers (see fig. 1). The calorimeter, trigger, and tracking system of the AFS have been described elsewhere [1,8]. For this analysis, only the roof calorimeter was used in the trigger. The energy resolution is $16\%/\sqrt{E}$ for electromagnetic showers and 30% at 1 GeV ($37\%/\sqrt{E}$ above 2 GeV) for hadronic showers. The estimated uncertainty in our absolute energy scale for isolated showers is 4%. For the analysis, a fiducial volume of 1.7 sr covering $\pm 36^\circ$ (32°) in azimuth for electromagnetic (hadronic) showers and ± 0.93 in rapidity (y) was used.

The trigger was formed by the addition of the pulse heights detected in the calorimeter, with each signal suitably weighted to transform to transverse energy (E_T) in the centre-of-mass system. In addition we required a minimum multiplicity

of 2 hits in the 44-element hodoscope (IH) surrounding the interaction region. Upstream and downstream counters (BB), covering $2^\circ < \theta < 6^\circ$ in polar angle, were used to monitor the luminosity. The integrated luminosity for the $\sqrt{s} = 45$ GeV data was $1.23 \times 10^{35} \text{ cm}^{-2}$, and the average luminosity during data-taking was $6.3 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$.

The data obtained were processed through our standard tracking and vertex reconstruction programs for charged particles in the central detector. We removed background from beam-gas events, cosmic-ray events, and pile-up, using the same procedure as in ref. 1, with an additional requirement on timing of the local energy deposit in the calorimeter. This new requirement, when imposed on the 63 GeV data [1], removed 3% of the events with $E_T > 12.5$ GeV. When imposed on the present data it removed 7% of the events with $E_T > 10.5$ GeV and less than 1% of the events at lower E_T . At the highest E_T , all these cuts removed 35% of the raw data, and we estimate a residual background contamination of less than 5%.

For the analysis of the calorimeter information, we used a pattern recognition program to reconstruct additional showers, with a spatial resolution of 1 cm for electromagnetic showers and 3-10 cm (depending on the incident angle) for hadronic ones. The transverse energy E_T was calculated by summing the transverse energy of the individual showers. Only events with more than 85% of their E_T in the fiducial volume were used. The E_T spectra for the two centre-of-mass energies are shown in fig. 2. The spectra are uncorrected for resolution, effects of energy leakage, and different calorimeter response to hadronic and electromagnetic showers. The errors shown are statistical only.

The data were divided into bins of E_T to study the spatial distribution of energy in the calorimeter wall. For each event a vector sum $\vec{E}'$ was formed by summing the highest energy clusters, making up $\geq 80\%$ of the E_T in the wall. Events were accepted if, in the laboratory frame, $\vec{E}'$ pointed to within $\pm 25^\circ$ in azimuth, and $\pm 30^\circ$ in polar angle, of the centre of the wall. Over 80% of the events satisfy these requirements. For these selected events, all the clusters in the wall were then used to calculate a quantity analogous to thrust T :

$$T = \sum \hat{E}' \cdot \vec{E}_i / \sum |\vec{E}_i| ,$$

where sums were carried out over all clusters; $\hat{E}'$ is the unit vector along $\vec{E}'$, and $\vec{E}_i$ are the individual cluster energy vectors; T is not explicitly maximized by variation of the $\hat{E}'$ direction and can take on values between 0.7 and 1.0. A pencil-like jet has $T \approx 1$, and highly isotropic events have $\langle T \rangle \approx 0.86$. The minimum value of T , $T = 0.7$, corresponds to an event with maximally separated showers within the calorimeter wall.

In fig. 3 we show $\langle T \rangle$ as a function of E_T for both $\sqrt{s} = 45$ and 63 GeV. For the lower E_T bins the average thrust is consistent with that expected for isotropic events ($\langle T \rangle \approx 0.86$); however, there is a clear rise in $\langle T \rangle$ as E_T increases. In fig. 4 we show the thrust distributions for a few E_T bins for both values of $\sqrt{s}$. The shape of the thrust distributions at the two energies are quite different at the highest values of E_T . Both data sets clearly deviate from what is expected for isotropic events by building up a high-thrust component. However, at $\sqrt{s} = 45$ GeV, this component does not dominate to the same degree as it does at $\sqrt{s} = 63$ GeV.

In order to obtain a jet cross-section, the fraction of events consistent with a hard-scattering constituent model is extracted from the shapes of the thrust distributions. This technique worked well for the $\sqrt{s} = 63$ GeV data, where clear evidence for the two components was observed in the thrust distribution. This is less evident in the $\sqrt{s} = 45$ GeV data, but for the purpose of comparison we use the same technique. Events with and without a hard-scattering constituent are generated using ISAJET [9], passed through a full simulation of the calorimeter response [10,11], and processed through our normal analysis chain.

ISAJET produces events using standard QCD perturbation theory in the leading log approximation. The events are composed of two high- p_T jets and two beam-jets fragmenting according to the Feynman-Field model [12]. The jet production and fragmentation are decoupled. The parton structure functions used are those of Baier et al. [13]. In the fragmentation process of high- p_T partons, a hard gluon may be emitted.

In the fit we assume that the thrust distributions have two components. The first component (jet) is described by hard-scattering constituents. The second component (non-jet) has a more isotropic event shape with a thrust distribution essentially the same as that observed for the events in the low E_T bins. In this paper we do not attempt to investigate further the detailed nature of the events attributed to the non-jet component.

Using these two components we fit the thrust distribution to obtain the relative jet-to-non-jet contribution in each E_T bin. As stated earlier, the results show a higher percentage of jet events for a given E_T bin at $\sqrt{s} = 63$ GeV. As $\sqrt{s}$ decreases and if this trend continues, the separation of the jet fraction from the rest of the events, using this or a similar method, will become more difficult [6].

Using the ISAJET Monte Carlo events and the detector simulation described above, we were able to relate the initial jet p_T to the E_T detected in the calorimeter. This together with the fit results enables us to transform the observed E_T spectrum into the p_T spectrum of the produced jet. The resulting inclusive jet production cross-section at $y = 0$ is shown in fig. 5 together with the results obtained at $\sqrt{s} = 63$ GeV [1] (see also Table 1). The inner errors reflect the statistical error of the fit and correction procedure. The outer errors include systematics, uncertainties in luminosity ($\pm 4\%$), model dependence of the Monte Carlo and representation of the detector (3.5% to 2%), and uncertainties in the energy scale (5% to 3.5%). An exponential fit, $\exp(-bp_T)$ at $\sqrt{s} = 45$ GeV gives a value for $b = 1.35 \pm 0.14$ GeV $^{-1}$, which is steeper than the observed slope 1.02 ± 0.09 GeV $^{-1}$ at $\sqrt{s} = 63$ GeV. The dotted lines in fig. 4 are the ISAJET predictions for the jet cross-section. The agreement in both shape and absolute normalization is good.

To parametrize the cross-section as a function of energy, we have fitted our data to a function of the form $A(1-x_T)^m \cdot p_T^{-n}$ (where $x_T = 2p_T/\sqrt{s}$) which has previously been used to fit single-particle high- p_T cross-sections. The results of the fit give values of $A = (1.6 \pm 1.0) \times 10^{-26}$, $m = 10.6 \pm 1.0$, and $n = 5.3 \pm 0.2$,

where only the statistical errors are included. Since one expects that at low- x_T the pp and $p\bar{p}$ jet cross-sections will be essentially the same, we also compare our results with the $p\bar{p}$ data at $\sqrt{s} = 540$ GeV [3]. In fig. 5 we show the three measurements of the jet cross-section as a function of x_T multiplied by p_T^n , where $n = 5.3$. The dotted line in fig. 5 shows the π^0 cross-section [14] multiplied by p_T^n ($n = 8$). It can be seen that the shape of the resulting x_T dependence is similar for both jet and π^0 cross-sections. A possible interpretation is that the $f(x_T)$ describes the convolution of the proton constituent structure functions, which is expected to be similar for jet and single-particle production, whilst the difference in the p_T power can be attributed to the fragmentation.

In this paper we have reported on the jet cross-section at $\sqrt{s} = 45$ GeV. The jet differential cross-section is lower and steeper at $\sqrt{s} = 45$ GeV than at $\sqrt{s} = 63$ GeV. The observed fraction of events at a given E_T , which are clearly dominated by jet production, is lower at $\sqrt{s} = 45$ GeV than at $\sqrt{s} = 63$ GeV. If this trend continues, the identification and separation of the jet component at lower $\sqrt{s}$ will become increasingly difficult. At both energies, the shape and the magnitude of the measured cross-section are well described by a QCD-motivated model.

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Support from the Research Councils in our home countries is gratefully acknowledged.

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Table 1

Cross-sections for single inclusive jet production.
Errors include both statistics and systematic effects.

$\sqrt{s} = 45 \text{ GeV}$		$\sqrt{s} = 63 \text{ GeV}$	
$P_T \text{ (GeV/c)}$	$E \, d\sigma/dp^3 \text{ (cm}^2/\text{GeV}^2)$	$P_T \text{ (GeV/c)}$	$E \, d\sigma/dp^3 \text{ (cm}^2/\text{GeV}^2)$
6.4	$(3.04 \pm 1.45) \times 10^{-32}$	6.66	$(7.02 \pm 2.35) \times 10^{-32}$
7.6	$(3.86 \pm 0.85) \times 10^{-33}$	7.96	$(1.07 \pm 0.45) \times 10^{-32}$
8.7	$(7.62 \pm 2.58) \times 10^{-34}$	9.16	$(3.61 \pm 0.69) \times 10^{-33}$
9.4	$(3.90 \pm 1.17) \times 10^{-34}$	10.46	$(8.84 \pm 1.80) \times 10^{-34}$
11.0	$(4.68 \pm 2.47) \times 10^{-35}$	11.46	$(2.42 \pm 0.47) \times 10^{-34}$
		12.85	$(9.00 \pm 1.33) \times 10^{-35}$

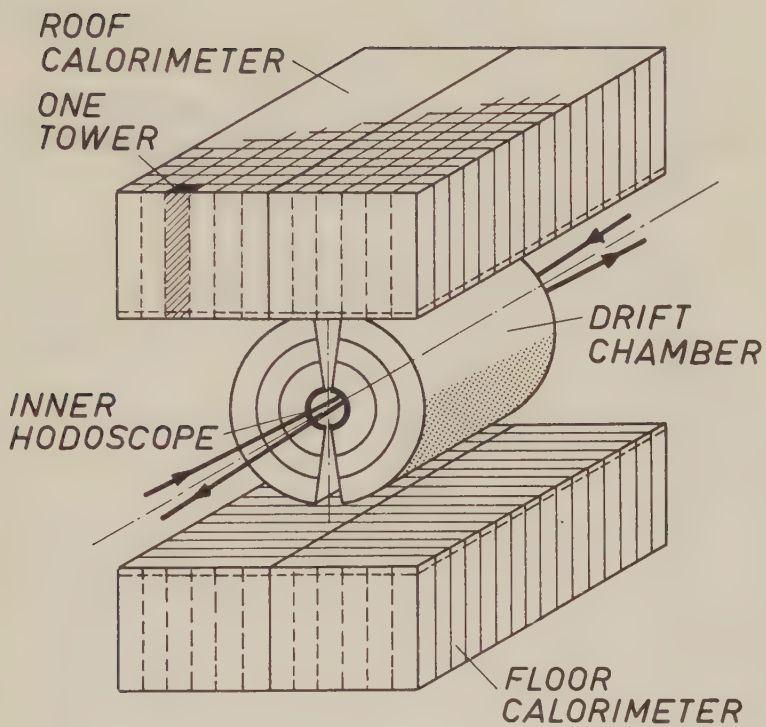


Fig. 1 : Experimental set-up.

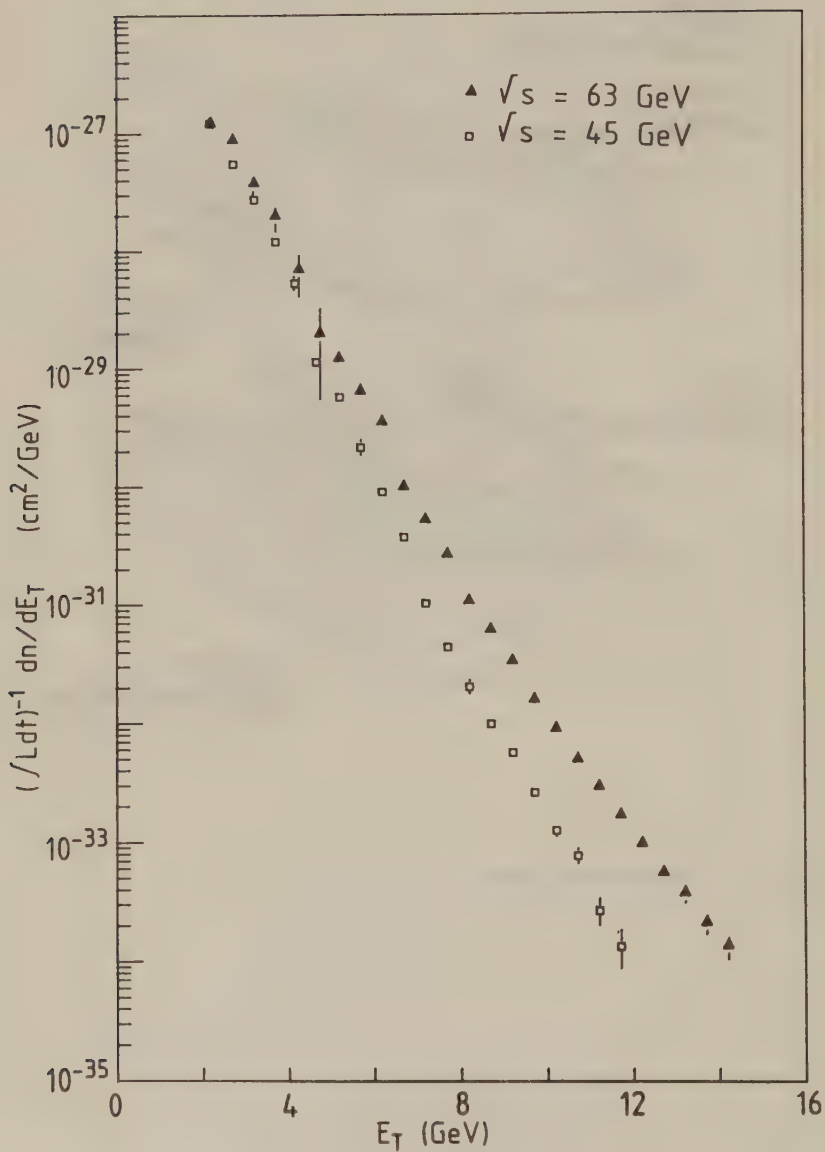


Fig. 2 : The uncorrected transverse energy spectrum; error bars are statistical only.

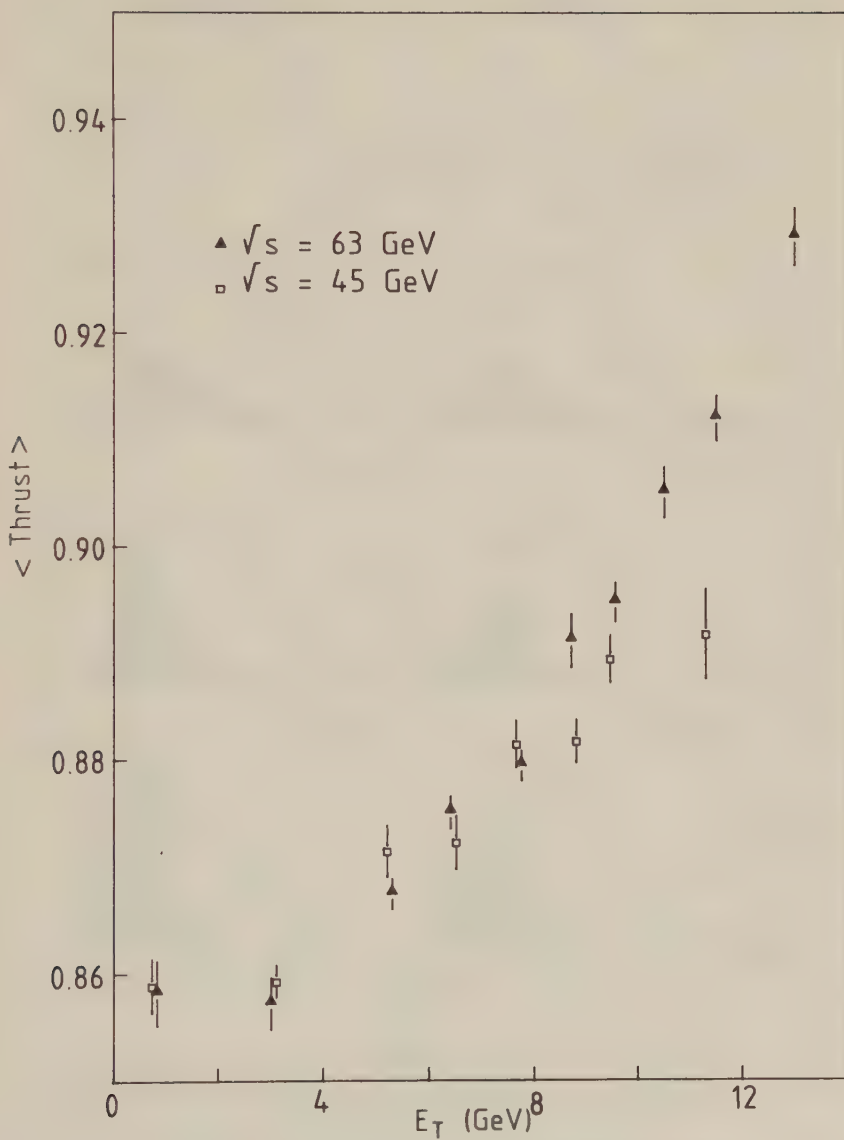


Fig. 3 : Mean thrust versus E_T .

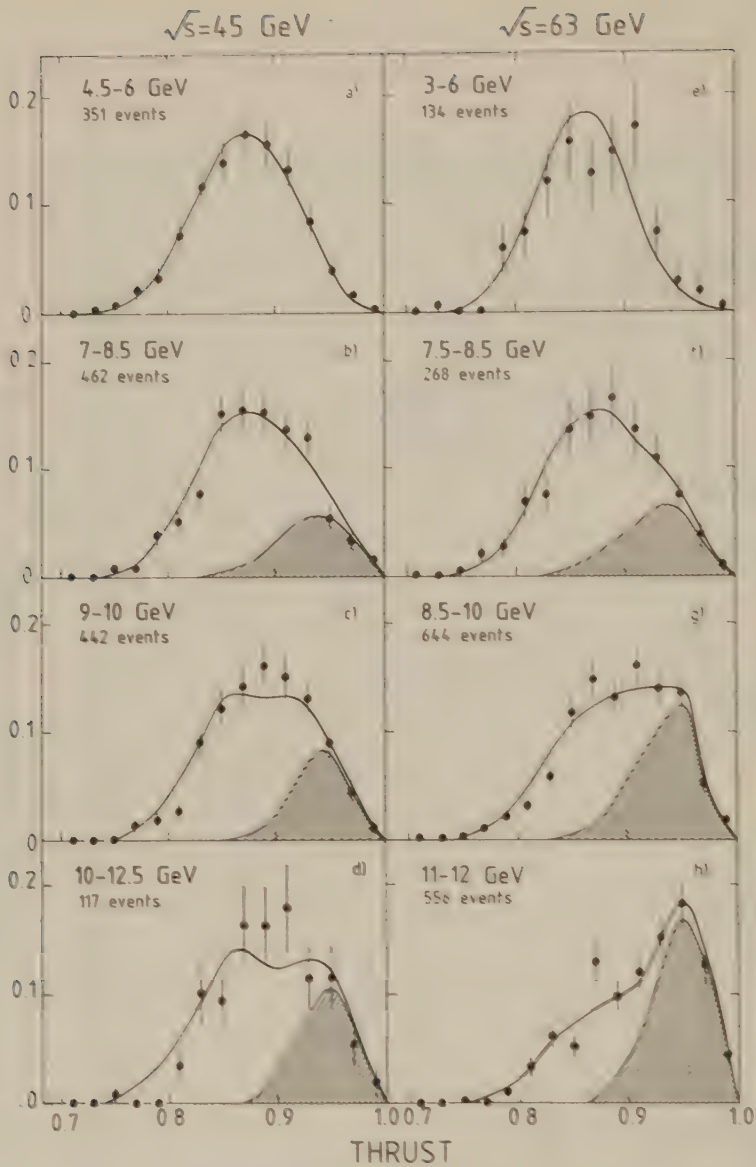


Fig. 4 : The fraction of events per 0.02 units of thrust for bins in E_T for $\sqrt{s} = 45$ GeV (a-d) and for $\sqrt{s} = 63$ GeV (e-h). Shaded region represents the contribution of the jet component; the solid curve shows the total fit.

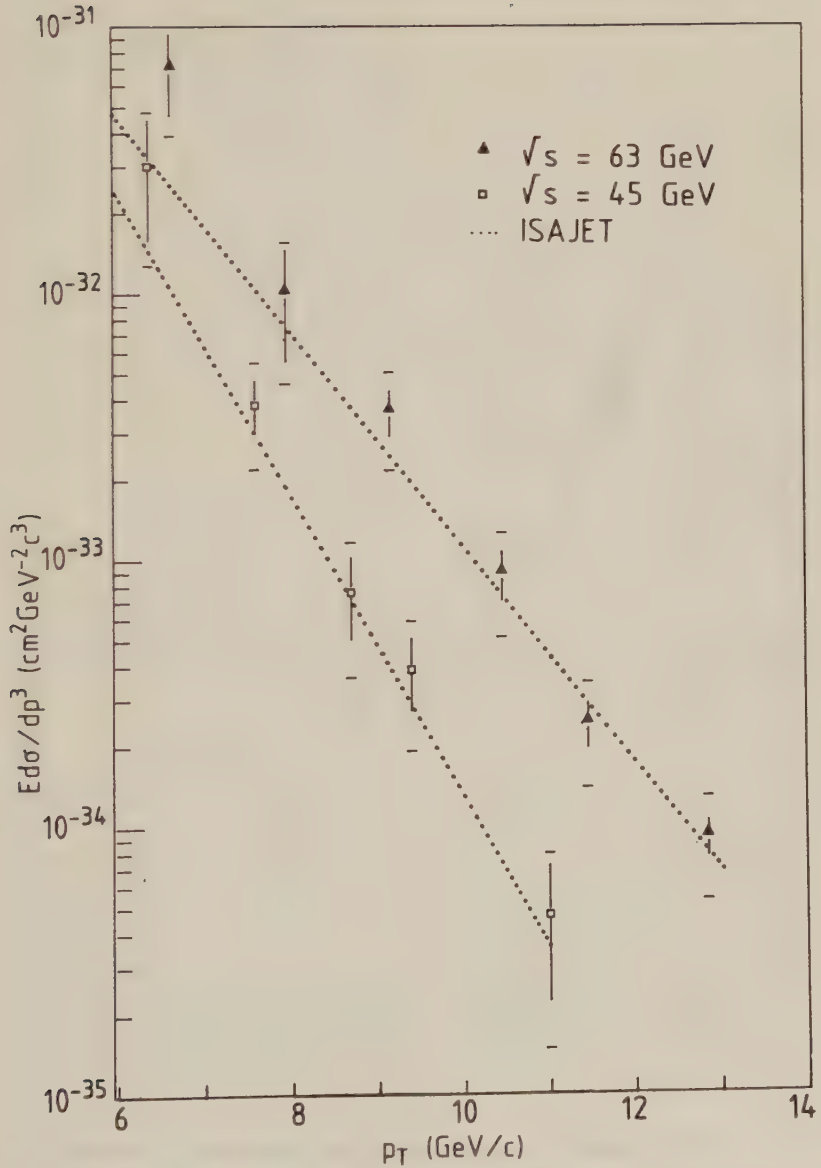


Fig. 5 : Invariant jet cross-section at $y = 0$ versus p_T . Outer errors include systematic effects. The dotted lines are theoretical predictions [9].

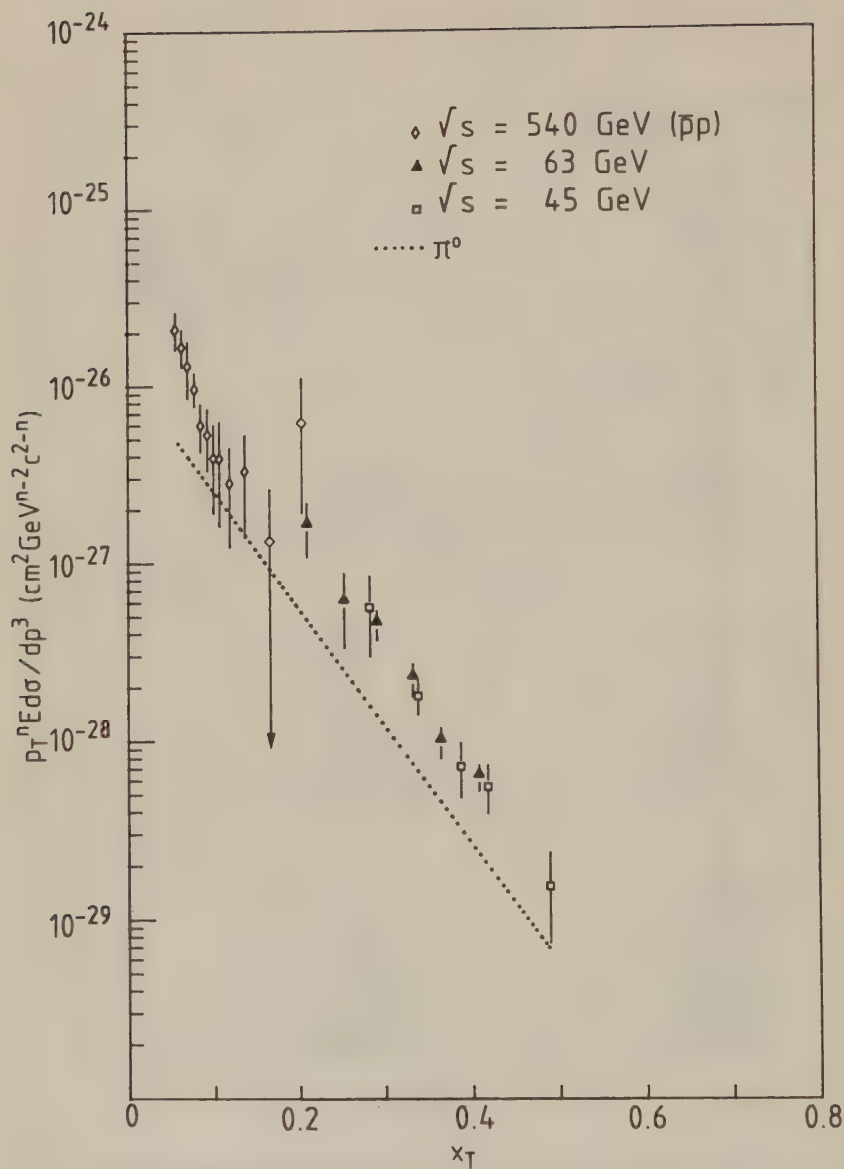


Fig. 6 : The invariant jet cross-section multiplied by $p_T^{5.3}$ versus x_T , including the data of ref. 3. Also shown is the π^0 cross-section at $\sqrt{s} = 63 \text{ GeV}$ [14] multiplied by p_T^8 .

A COMPARISON OF $\bar{p}p$ AND pp INTERACTIONS IN THE CENTRAL REGION AT $\sqrt{s} = 53$ GeV

The Axial Field Spectrometer Collaboration

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The inclusive production cross sections of pions, kaons, protons, and antiprotons in $\bar{p}p$ and pp interactions at $\sqrt{s} = 53$ GeV are compared in the kinematic range $|y| < 0.8$ and $p_T < 1.5$ GeV/c. We observe differences in the K^+/K^- and $\bar{p}/p$ ratios for the two data samples. Although the bulk of the particles are produced with the same transverse momentum and rapidity distributions in $\bar{p}p$ and pp collisions, we observe difference in these distributions for produced protons and antiprotons.

This experiment was performed at the CERN Intersecting Storage Rings (ISR) using the Axial Field Spectrometer [1,2]. For the data reported here, the momentum measurements were made in a cylindrical drift chamber with multiple ionization sampling (dE/dx), which is used for particle identification. Good $\pi^\pm$, $K^\pm$, and $\bar{p}p$ discrimination is obtained for non-relativistic particles. Protons and antiprotons are identified in the range $200 < P_{lab} < 800$ MeV/c, and $K^\pm$ mesons in the range $100 < P_{lab} < 500$ MeV/c [2].

The vertex detector is a 1.4 m long drift chamber of the "bicycle wheel" configuration with 4° azimuthal segmentation. Each 4° sector contains 42 resistive

sense wires that provide the coordinates in the transverse plane from drift time, and the position along the sense wire from charge division measurement.

The resolution in the chamber is $\sigma = 230 \mu\text{m}$ (r.m.s.) in drift distance and $\sigma = 1.5$ cm (r.m.s.) in the axial coordinate. For dE/dx measurements, the truncated mean (for > 30 pulse-height measurements) for minimum ionizing tracks has $\sigma_{rms}/\text{mean} = 11\%$.

The data described here consist of 25000 $\bar{p}p$ events and 36000 pp events at $\sqrt{s} = 53$ GeV. Both samples were obtained in ISR runs with low luminosity, spaced closely in time, and analysed with the same set of analysis programs. The trigger used was a minimum bias trigger, defined by a coincidence between scintillation counters surrounding the two beam pipes down-

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stream of the intersection region. This trigger is sensitive to approximately 60% of the inelastic interactions. Background from beam-gas and beam-pipe interactions was measured by running with only the proton beam present, and processing the events accepted by our trigger through the off-line analysis program. We conclude that for both data samples this background is less than 1%.

We have determined that our acceptance is essentially uniform in the rapidity region $|y| < 0.8$ and in 76% of our azimuthal coverage. Thus all distributions presented will be for this region. The uncertainty in absolute normalization is approximately 10%; however, most results are presented as ratios of $\bar{p}p$ cross sections relative to pp cross sections.

In fig. 1, the p_T spectrum of charged secondaries obtained in this experiment for pp collisions is shown together with the spectrum observed at 90° in previous experiments [3-5]. The distributions agree well, given that both distributions have absolute normalization uncertainties of 10%. Fig. 2a shows the p_T spectra for $\bar{p}p$ and pp collisions, and the ratio of the distributions in fig. 2b shows that there are no large ($\geq 10\%$) differences in the p_T distribution of charged secondaries up to 1.5 GeV/c, although we do observe a slight depletion ($5.7 \pm 1.3\%$ in $0.7 < p_T < 1.5$ GeV/c) of high p_T particles in $\bar{p}p$ collisions (relative to pp). An exponential fit $\exp(-ap_T)$ to the p_T spectra ($0.3 < p_T < 1.5$ GeV/c) gives $a = 3.70 \pm 0.03$ (GeV/c) $^{-1}$ for $\bar{p}p$ collisions

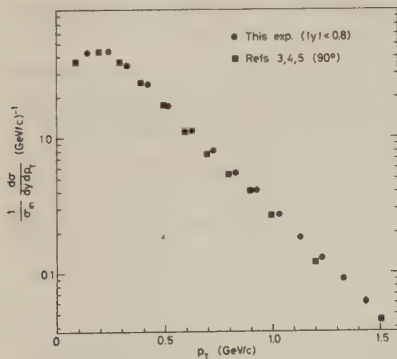


Fig. 1. Comparison of $(1/\sigma_{\text{in}})(d\sigma/dy dp_T)$ versus p_T obtained in this experiment ($|y| < 0.8$) with results of refs. [3-5].

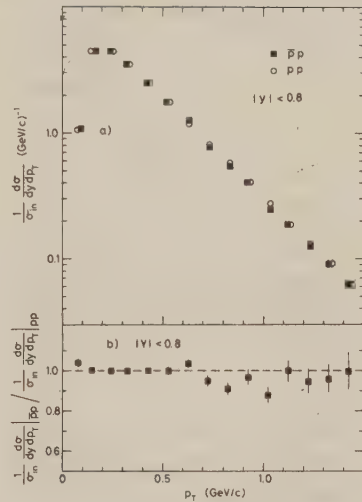


Fig. 2. (a) $(1/\sigma_{\text{in}})(d\sigma/dy dp_T)$ versus p_T for $\bar{p}p$ and pp collisions in the region $|y| < 0.8$. In cases of overlap the points have been displaced equally sideways. (b) Ratios of average multiplicity per unit p_T versus p_T .

and $a = 3.63 \pm 0.02$ (GeV/c) $^{-1}$ for pp collisions.

The charged particle multiplicity distributions in our acceptance for $\bar{p}p$ and pp collisions are shown together in fig. 3a, and their ratio in fig. 3b. The average charged multiplicity per unit rapidity in the region $|y| < 0.8$, is $\langle n_{\text{ch}} \rangle_{pp} = 2.31 \pm 0.01$ and $\langle n_{\text{ch}} \rangle_{\bar{p}p} = 2.30 \pm 0.01$, and the shapes of the distributions are also consistent with being identical, although there may be a surplus of high multiplicity events in $\bar{p}p$ interactions. The curves in fig. 3b show the expected behaviour if the difference in $\bar{p}p$ and pp cross section ($\Delta\sigma$) results from a component with a higher central multiplicity parametrized by $\langle n_{\text{ch}} \rangle_{\bar{p}p,a} = \langle n_{\text{ch}} \rangle_{pp} + \epsilon$, where $\Delta\sigma$ is estimated to be 0.9 mb and KNO scaling is used to determine the distribution of this component.

The ratio of the average multiplicity per unit rapidity interval in $\bar{p}p$ and pp collisions is shown as a function of y in fig. 4 for all charged particles and for positive and negative particles separately. There are significantly more negative particles in $\bar{p}p$ collisions (than

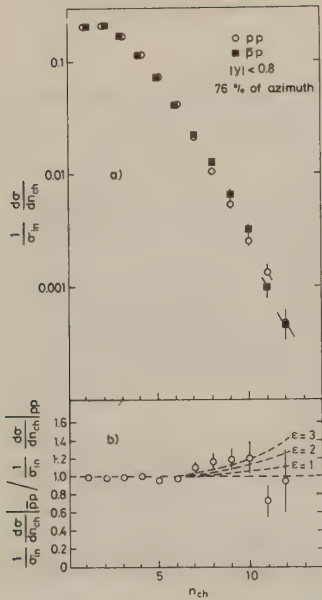


Fig. 3. (a) Charged particle multiplicity of $\bar{p}p$ and pp collisions in the region $|y| < 0.8$ and 76% of azimuth. In cases of overlap the points have been displaced equally sideways. (b) $(1/\sigma_n)(d\sigma/dn_{ch})|_{\bar{p}p}/(1/\sigma_n)(d\sigma/dn_{ch})|_{pp}$. The curves are estimates of the ratio assuming that the $\bar{p}p$ annihilation events have $(n_{ch})_{\bar{p}p} = (n_{ch})_{pp} + e$ (see text).

in pp) and fewer positive particles, which is to be expected since in $\bar{p}p$ collisions the $+/-$ ratio must equal 1.0 at $y = 0$ (we observe 0.98 ± 0.01), whilst in pp interactions it exceeds 1.0 by a few percent (we observe 1.03 ± 0.01 , and refs. [3–5] find 1.06 ± 0.01). However, no y -dependence is observed within our range $|y| < 0.8$. The values of these ratios averaged over the range $|y| < 0.8$ are summarized in table 1, where the corresponding values for $K^+ + K^-$ and $p + \bar{p}$ are also presented.

In the pp sample we observe a K^+/K^- ratio of 1.24 ± 0.06 , in good agreement with a previous measurement [5], where the value obtained at 90° is 1.18 ± 0.06 . In the $\bar{p}p$ sample the K^+/K^- ratio is found to be 1.04 ± 0.07 , close to the expected value of 1.

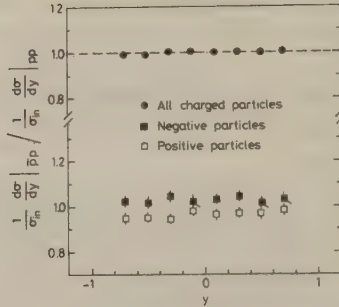


Fig. 4. Ratio of the average charged particle multiplicity per unit y versus y .

From table 1 we see that the total kaon production in the same, within errors, in $\bar{p}p$ and pp interactions. However, we note that there are $8 \pm 6\%$ more K^- and $10 \pm 5\%$ fewer K^+ emitted into the region $|y| < 0.8$ from $\bar{p}p$ interactions. Within errors this difference is independent of rapidity and transverse momentum.

These observations are in good agreement with the expected difference in (K, Y) associated production and with no change in the (K, K) pair production. The contribution to the kaon production in our region from (K, Y) associated production is $\approx 20\%$, as measured by the K^+/K^- ratio in pp interactions. From this one would expect $\approx 10\%$ and more K^- and $\approx 10\%$ less K^+ in $\bar{p}p$ than in pp collisions.

For proton and antiproton production we also observe a difference between $\bar{p}p$ and pp interactions. In this instance there is an indication of a difference in

Table 1

Ratio of average charged particle multiplicity for $|y| < 0.8$.

	$\langle n \rangle_{\bar{p}p} / \langle n \rangle_{pp}$
all ($\pm$)	1.00 ± 0.01
+	0.96 ± 0.01
-	1.03 ± 0.01
$K^+ + K^-$	0.98 ± 0.04
K^+	0.90 ± 0.05
K^-	1.08 ± 0.06
$p + \bar{p}$	1.05 ± 0.04
p	0.93 ± 0.04
$\bar{p}$	1.25 ± 0.07

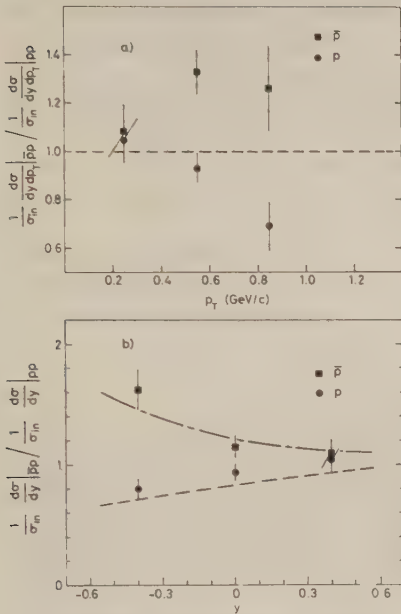


Fig. 5. Comparison of proton and antiproton production. The curves in (b) are the expected $\bar{p}$ (---) and p (---) y -dependence obtained from the measured $pp \rightarrow pX$ and $pp \rightarrow \bar{p}X$ cross sections (see text).

the p_T and y dependence of the ratio, as can be seen in fig. 5. The broken lines in fig. 5b are the estimates of the expected y -dependence obtained from the measured $pp \rightarrow pX$ and $pp \rightarrow \bar{p}X$ cross sections [5] at $p_T = 0.6$ GeV/c, which are shown schematically in fig. 6, curves (a) and (b). The difference between (a) and (b) gives the sum of the beam fragmentation distributions (c), which can be decomposed into the symmetric curves (d_L) and (d_R) by assuming that the beam fragmentation extends to $|y| = 1$ in the backward hemisphere^{†1}. Then the assumption that pair production

^{†1} Precise data would enable the beam fragmentation distributions [curves (d)] to be extracted directly from the data. It is already clear from the modest y -variation of the data that the beam fragmentation distributions must extend significantly (approximately 1 unit in y) into the backward hemisphere.

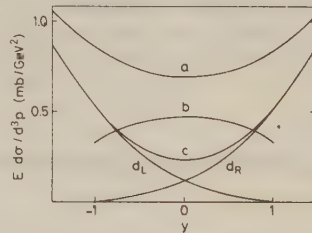


Fig. 6. Cross sections used in obtaining the broken lines shown in fig. 5b. Curve (a): $pp \rightarrow pX$; curve (b): $pp \rightarrow \bar{p}X$; curve (c): the difference between distributions (a) and (b), which is equal to the distribution of protons from the beam fragmentation; curves (d_L) and (d_R) are the decomposition of curve (c) into left-moving and right-moving beam fragmentation distributions, respectively.

of protons and antiprotons is identical in pp and $\bar{p}p$ interactions and that the beam fragmentation $p \rightarrow p$ and $\bar{p} \rightarrow \bar{p}$ has the same y and p_T distributions allows one to calculate the ratio shown in fig. 5b.

We conclude that within the statistical errors of our event sample, distributions in charged particle multiplicity, rapidity, and transverse momentum in $\bar{p}p$ and pp interactions at $\sqrt{s} = 53$ GeV, $|y| < 0.8$, and $p_T < 1.5$ GeV/c are similar except for such changes in charge and baryon number flow, which can be understood as being consequences of the change in quantum numbers of one of the colliding particles. In particular, we have not observed any increase of the pair production of K^+ or protons and antiprotons in $\bar{p}p$ interactions, since the total production of kaons ($K^+ + K^-$) and of protons and antiprotons ($\bar{p} + p$) is the same for the two data samples. The observations reported here do not of course exclude differences between $\bar{p}p$ and pp collisions in rare final states.

These results were made possible by the fine achievements of the CERN Proton Synchrotron and Intersecting Storage Rings Divisions and the Antiproton Accumulator Group, in successfully producing, cooling, accelerating, and storing antiprotons in the ISR. We acknowledge with thanks the work of the CERN Experimental Facilities Division on the drift chamber construction, and that of the Experimental Support Group of the ISR Division who installed the experiment. A large number of people have worked on the

construction of the Axial Field Spectrometer and we would like to thank them all. Support from the Research Councils in our home countries is gratefully acknowledged.

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Performance of the AFS-Vertex Detector at the CERN ISR

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Abstract

The central detector of the Axial Field Spectrometer (AFS) is a cylindrical drift chamber using a "bicycle-wheel" geometry. Its design has been optimized for jet-like events with high track densities. This is accomplished through a high degree of azimuthal segmentation (4° sectors) with up to 42 space points per track, using measurements of drift time and charge division. Particle identification in the non-relativistic region is obtained by (dE/dx) sampling. The detector is operated in an inhomogeneous magnetic field at event rates of typically $> 5 \times 10^5$ collisions per second. Preliminary results will be presented on the detector performance achieved after the first months of operation at the ISR.

1. Introduction

The Axial Field Spectrometer (AFS) at the CERN ISR (Fig. 1) was developed to study events characterized by a large transverse momentum ("high p_T "). This required a vertex detector with the following properties: low mass to minimize interference with surrounding detectors, good momentum resolution, powerful pattern recognition for high track densities and event rates and particle identification in the non-relativistic region [1].

For this purpose, a cylindrical drift chamber was constructed with 4° azimuthal segmentation. The chamber is 1.4 m long and extends from a radius of 0.2 m to 0.8 m. Each 4° sector contains 42 resistive sense wires (arranged radially into three crowns) with linear amplifiers at each end, allowing non-projective space point reconstruction by drift time and charge division measurement. In addition, the sums of the pulse heights per wire are used for particle identification by multiple ionization sampling (dE/dx) . The sense wires are staggered by ± 0.4 mm to resolve the left-right ambiguity from the drift time measurement.

Details of the chamber construction and the electronics may be found in earlier papers [2, 3]. Figure 2 gives a view of one half-chamber, Fig. 3 shows details of the geometry.

We will present preliminary results on the performance of the detector at the ISR. As the complete detector has been in operation for only five months, we are confident that considerable improvement is still possible, especially in the spatial resolution.

2. Operation

The chamber is operated with a 50/50% mixture of argon/ethane at atmospheric pressure. The gas amplification is adjusted to $(3-6) \times 10^4$. This value is a compromise between acceptable chamber life-time and particle identification on one hand, and space resolution on the other. It is known [4] that saturation effects – dependent on track angle – appear once an avalanche contains more than about 10^6 electrons. More serious are gas ageing effects: a 15% reduction in gas amplification has been observed in a test chamber after a total irradiation of $3 \times 10^{16} \text{ e mm}^{-1}$ corresponding to about 2 yr of ISR operation at present luminosities. On the other hand, higher gas amplification improves the time resolution (less time slewing) and especially the resolution from charge division (determined by the signal/noise ratio).

The gas system monitors the gas mixture, oxygen and water contamination and gas amplification with a test chamber.

Due to the open structure of the magnet, the outer section of the chamber experiences magnetic field inhomogeneities of more than 30%, which are, however, independent of azimuth.

The average drift field is 1.25 KV cm^{-1} .

3. Performance

3.1. Crosstalk

The capacitive crosstalk between adjacent channels is $\leq 1\%$. For track signals a larger pulse of opposite sign is induced by the movement of the electrons and ions in the avalanche. This chamber crosstalk depends on the geometry and changes from the inner to the outer wires. The total crosstalk was measured to rise with radius from -4 to -6% between adjacent wires and from -0.5 to -2% between a wire and its second closest neighbour.

This crosstalk affects mainly the drift time and dE/dx measurements.

3.2. Drift time measurement

The drift times are measured with CERN DTR units, which contribute $\sigma = 60 \mu\text{s}$ to the space resolution. At present, the resolu-

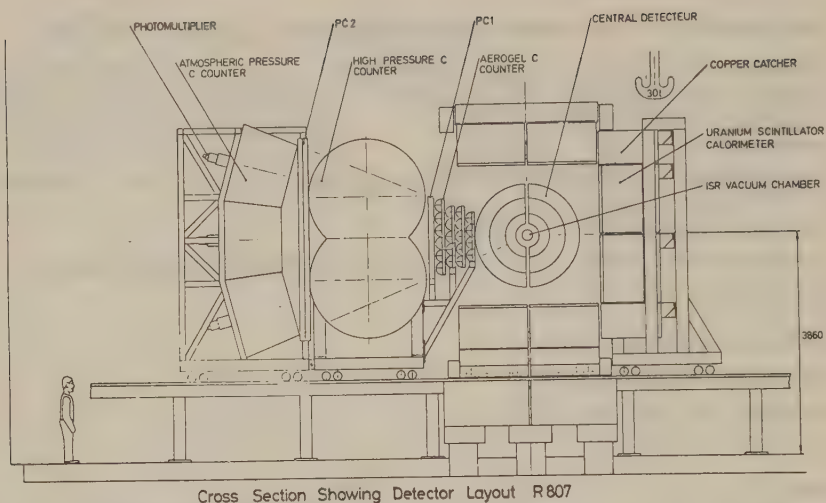


Fig. 1. General layout of the Axial Field Spectrometer.

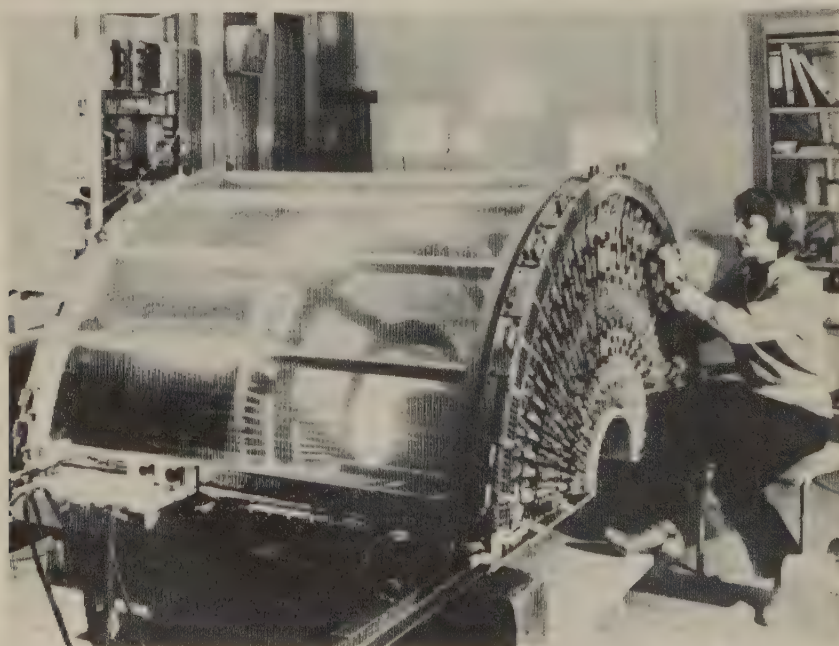


Fig. 2. View of one 180° drift chamber. The light is reflected from the 100 μ drift and potential wires and displays the segmentation into 4° sectors.

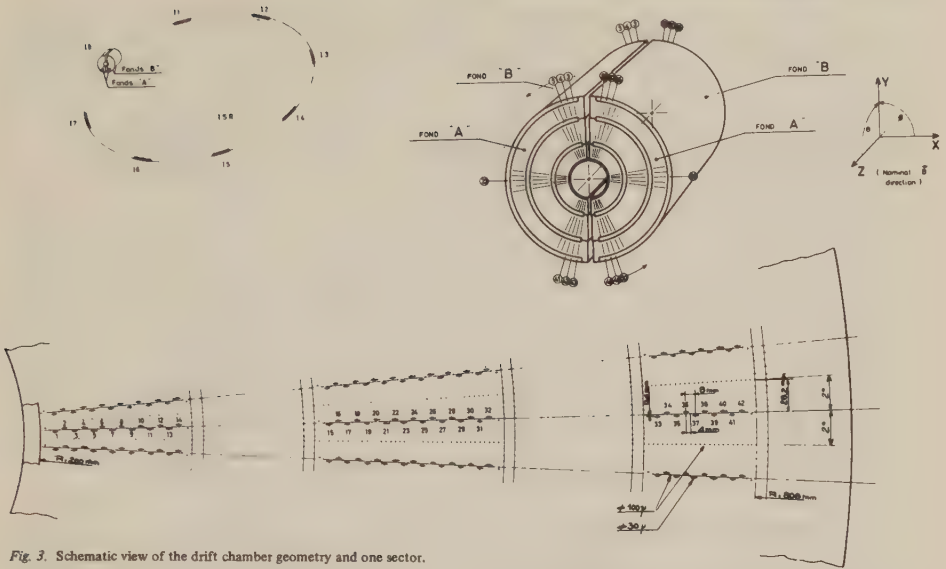


Fig. 3. Schematic view of the drift chamber geometry and one sector.

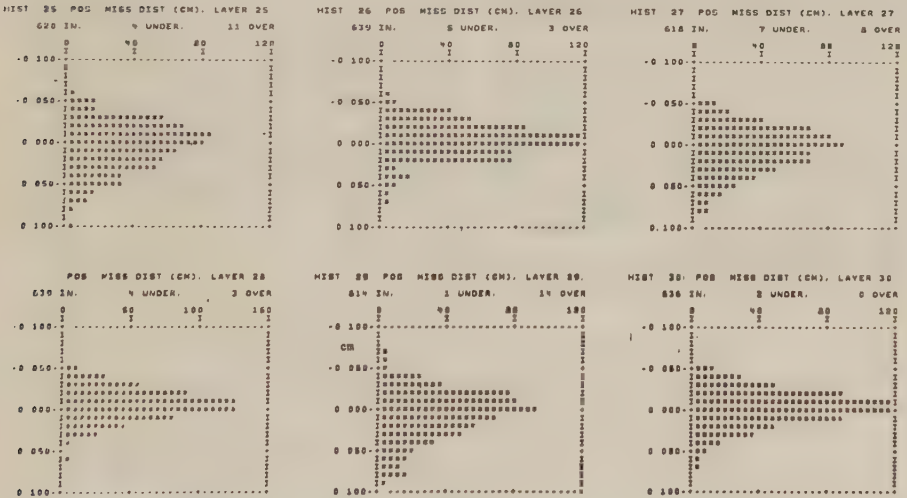


Fig. 4. Drift time resolution in radial layers 25 to 30. Tracks pass closer to the sense wires of the even layers (see also Fig. 3).

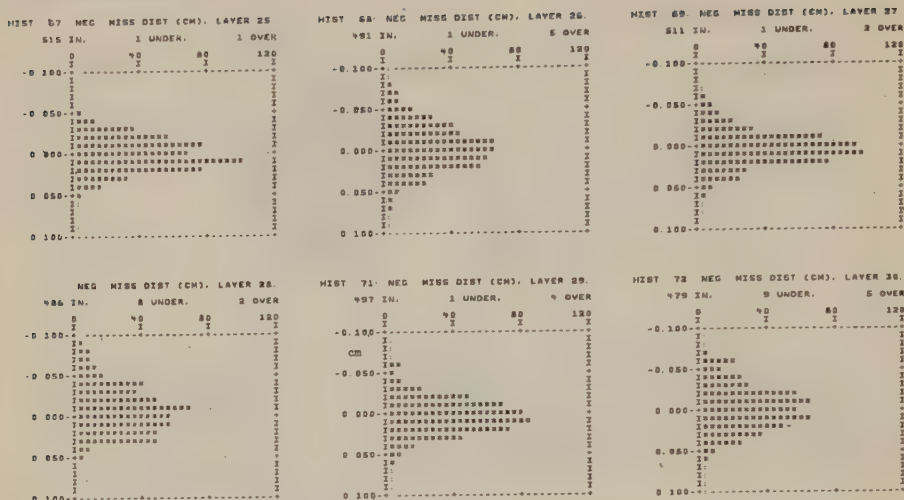


Fig. 5. As Fig. 4, but tracks pass closer to the odd sense wires.

ution for reconstructed tracks is $\sigma = 270 \mu$, averaged over the full azimuth and after making corrections for electrostatic wire deflections, magnetic field inhomogeneities and non-uniform drift velocity.

We expect to improve this resolution by introducing additional corrections for time slewing as a function of pulse height, crosstalk, drift distance and angle, for gravitational wire sag and by a more refined treatment for tracks close to the cell boundaries and sense wire planes.

An example of an uncorrected systematic effect is shown in Figs. 4–5. The distribution of deviations from reconstructed tracks is displayed for 6 of the 42 radial layers, for tracks passing above the sense wire planes in Fig. 4 and for tracks below the same planes in Fig. 5. The effect of the wire staggering is clearly visible: the resolution for wires close to the tracks (even layers in Fig. 4, odd layers in Fig. 5) is far better: $\sigma \leq 200 \mu$. Note also the asymmetry of the distribution for the far-side wires. Tracks crossing the sector boundaries or the sense wire planes were excluded.

These results point to what we consider to be our major uncorrected error: time slewing effects combined with cross-

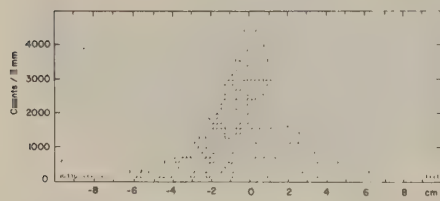
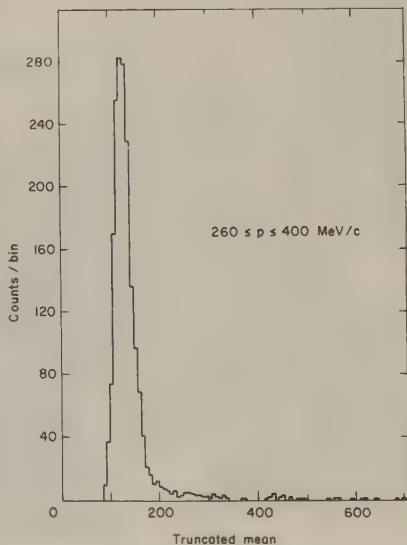


Fig. 6. z-resolution from charge division: FWHM = 3.4 cm.

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Fig. 7. dE/dx resolution. FWHM/truncated mean (60% of lowest pulse heights) = 27%. To the right of the pion peak may be seen hits from kaons and protons.

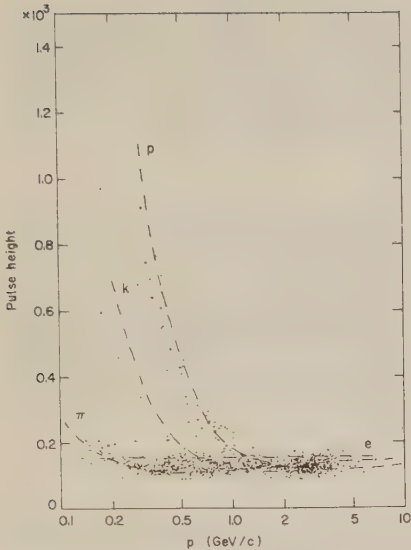


Fig. 8. dE/dx : truncated mean vs. momentum. Clear $\pi/K/p$ separation is achieved. The denser population for $p > 2.5$ GeV/c indicates a good efficiency of the event trigger, which was set at this momentum. The dashed lines were obtained with a program from [5].

talk. As we are operating at relatively low gas amplification, time slewing is significant for all wires. However, because of the sense wire staggering, corresponding to a drift time separation of 16 ns, the wires on the far side experience an additional time slewing due to crosstalk from the adjacent wires. The crosstalk pulses have enough time to develop before the avalanche reaches the far wire. For big pulses on the near wires, the additional slewing may amount to > 10 ns.

We are presently introducing corrections for these effects. They are complicated by their dependence on discriminator levels, drift distances, track angles and radial position of the wire.

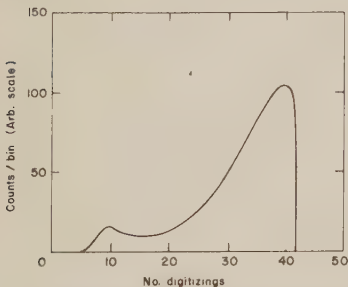


Fig. 9. Distribution of number of drift time digitizations for all tracks entering the Cherenkov arm (maximum = 42 wires).

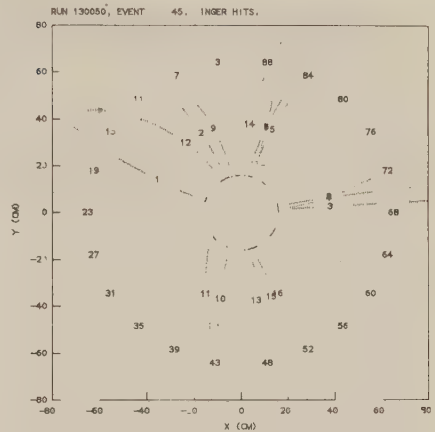


Fig. 10. High p_T event ($p_T = 4$ GeV/c for the triggering track No. 3). Shown are all points used in the track fitting.

3.3. Charge division

The resolution from charge division is essentially limited by the signal to noise ratio. Indeed, a strong correlation is found between pulse height (PH) and resolution along the wire: $\text{FWHM}(\text{cm}) = 1.3 + 200 \times \text{noise}/\text{PH}$. The average resolution for all reconstructed tracks is $\text{FWHM} = 3.4$ cm or $\text{FWHM}/\text{wire length} = 2.4\%$ (see Fig. 6). This is close to the value expected from the measured noise and pulse heights. In a test beam, $\text{FWHM}/\text{wire length} = 1.6\%$ was obtained with about half our present noise. Due to non-Gaussian tails the r.m.s. of the

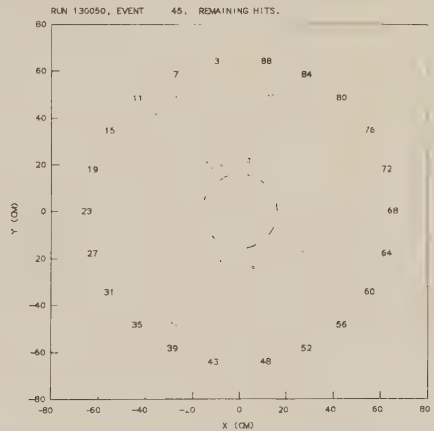


Fig. 11. Same event as in Fig. 10. Shown are points not used in the track fitting. Each point is displayed twice because of left-right ambiguity.

z -residue distribution is substantially larger than $\text{FWHM}/2.35$. We hope to improve the z -resolution by reducing the noise (mostly pick-up in the ISR intersection) and by additional corrections, e.g., for crosstalk.

3.4. Particle identification

Based on experimental data and Monte Carlo calculations on dE/dx resolution, we had expected for 42 samples of 8 mm: $\text{FWHM}/\text{mean} \geq 20\%$. With our present algorithms we obtain for the truncated mean of the 60% lowest pulse heights, $\text{FWHM}/\text{mean} = 27\%$ as an average for all tracks into the Cherenkov arm ($\pm 20^\circ$ in azimuth, see Fig. 1), which have ≥ 30 time digitizations and z -measurements, and which do not cross cell boundaries or sense wire planes. Figure 7 shows the distribution of the truncated means for the 60% lowest pulse heights. Crosstalk corrections have not been applied.

This resolution provides good particle identification in the non-relativistic region, as can be seen in Fig. 8. The dashed curves were calculated with a Monte Carlo program written by W. Scott and based on the model by Allison and Cobb [5].

We intend to add corrections for crosstalk and the dependence of pulse sharing between near and far wires on the drift distance.

3.5. Diverse

The track reconstruction efficiency is very high. On a sample of 200 high multiplicity events scanned by eye, all primary tracks above 50 MeV with more than 9 points were found.

However, clusters of points on tracks may be lost, e.g., because of a second close track. Figure 9 shows the distribution of the number of drift time digitizations used in the track fitting, for all tracks entering the Cherenkov arm. An event triggered on a high p_T particle is displayed in the last figures. Figure 10 shows the hits used in the track fitting; Figure 11 those rejected, both choices for the drift direction being drawn.

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Noted added in proof: The overall drift time resolution has been improved from 270μ to 200μ , mainly by first order corrections for time slewing and crosstalk.

APPENDIX

A Maximum Likelihood method for dE/dx analysis. (R807/229)

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Identification in the driftchamber

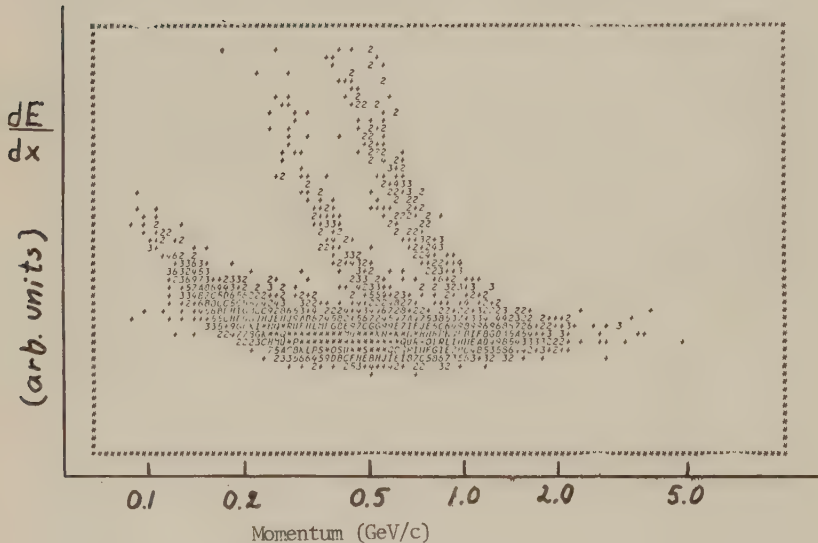
The dE/dx-routine in MARTHA is changed to give an enhanced possibility for using the ionization information in the jetchamber. In the future we will get the following things on the DST:

$\langle dE/dx, 70\% \text{ lowest} \rangle$ = The truncated mean of the 70% lowest pulseheights in the track.

The number of INGER and MARTHA accepted z-measurements in the track.

The absolute value of the logarithm of the likelihood-functions for electron, pion, kaon and proton hypothesis.

The probability that the particle making the track is an electron, pion, kaon and proton assuming equal production rates for the different particles and that there are no other particle sorts in the chamber.



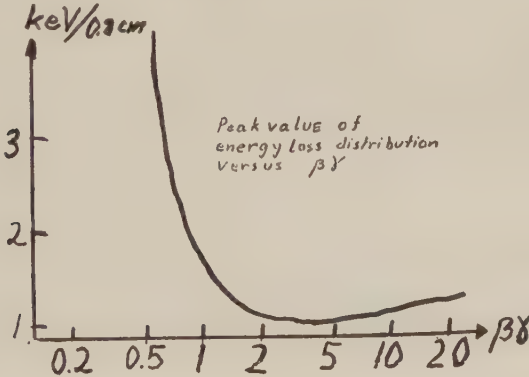
The Likelihood-functions

We know that the shape of the energy loss distribution varies with the particle-velocity, but the variation is rather small (about 7%) so we assume that the shape of the Landau-distribution is velocity independent, and take as our standard energy loss distribution, the one we have for minimum ionizing particles.



We get the distribution for the most probable energy loss from our data and parametrizes it with :

$$\langle dE/dx \rangle = C1 * (C2 * \ln(\beta\gamma) + C3) / \beta\gamma^2$$



We say that the energy loss distribution for a given velocity is the standard one, rescaled with the dE/dx -curve.

Now we could find the most probable energy loss $\langle dE/dx \rangle$, by maximizing the Likelihood-function with $\langle dE/dx \rangle$ as the variable.
The Likelihood-function is:

$$L(\langle dE/dx \rangle) = \prod_{i=1}^n f(\langle dE/dx \rangle, q(i))$$

where the $\{ q(i) \}$ are the pulseheight measurements,
and the $f(\langle dE/dx \rangle, q(i))$ is the probability for energy loss $q(i)$
for a Landau-distribution with peakvalue at $\langle dE/dx \rangle$.

Then we could see which particle assumption lies closest to this $\langle dE/dx \rangle$ value.

This would be a time consuming procedure to do on every track in our data, and since we know that there are only four sorts of particles in our chamber (ignoring muons, deuterons, quarks, monopoles etc), we can do something that is much faster.

We calculate the value of the Likelihood-functions for each of the four particle hypotheses because we know what the energy loss distribution for a given momentum looks like for each particleflavour. Then we do the maximum-likelihood by selecting biggest Likelihood-function.

For numerical reasons we calculate the absolutevalue of the logarithm of the likelihoodfunctions:

$|\ln(L(\langle dE/dx, \text{flavour} \rangle, \text{momentum}))| = \text{SUM}(|\ln(f(\langle dE/dx, \text{flavour} \rangle, q(i)))|)$
so the maximum likelihood is the minimum of these.

For translating the `lln(likelihoodfunction)` to an absolute probability we need a montecarlo.

```

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|*****>>| B L A C K - B O X |
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|         |
| V      | V      | V      | V      |
| V      | V      | V      | V      |
| L(e)   | L(pi)  | L(ka) | L(pr) |

```

Say that we have a black box into which we shoot repeatedly electron, pion, kaon and proton. For each particle that we shoot in there come out four numbers $L(e)$, $L(\pi)$, $L(k)$ and $L(p)$. For each time we shoot in an electron we observe if the value of $L(\pi)$, $L(k)$ and $L(p)$ is above L_0 , $L_0 + d_l$, $L_0 + 2 * d_l$, etc. If the value of $L(\pi)$ is above L_0 , a counter $N(\pi, L_0, \text{momentum}, \# \text{pulseheights})$ is incremented, if $L(\pi) > L_0 + d_l$, $N(\pi, L_0 + d_l, \text{momentum}, \#PH)$ is incremented etc. If $L(k) > L_0$, $N(k, L_0, \text{mom}, \#PH)$ is incremented etc. Each time we shoot in a pion we observe $L(e)$, $L(k)$ and $L(p)$. Each time we shoot in a kaon we observe $L(e)$, $L(\pi)$ and $L(p)$. Each time we shoot in a proton we observe $L(e)$, $L(\pi)$ and $L(k)$. This procedure is done for each momentum-bin and number of pulseheight-bin with about 2000 simulated tracks. After that the probability is defined as

$$P(\pi, L(\pi)) = \frac{L_0 + n * d_l, \text{momentum}, \#PH}{1 - N(\pi, L_0 + n * d_l, \text{momentum}, \#PH) / (3 * 2000)}$$

A track with 30 pulseheight measurements, $\text{momentum} = 1.0 \text{ GeV}/c$ and $L(\pi) = L_0 + 20 * d_l$ has a probability of

$$P(\pi, L_0 + 20 * d_l, 1.0, 30) \text{ percent to be a pion,}$$

where P is defined as above, and with the assumption of equal rates of pions, kaons, protons and electrons as the only types of produced particles.

The P's are generated with the described procedure in a montecarlo which generates pulseheights with the same pulseheight distribution as we have in our chamber.

The probabilities are easily understandable numbers that can be added to each other to form a joint probability for one track (that is an electron or a pion), or can be multiplied with each other to form a joint probability for two or more tracks. They can also be used to form a probability together with some other parts in the spectrometer, for example an electromagnetic shower and the probability for electron in the jetchamber.

Examples of identity requirements

Figure one to four shows the ionization plot for
 $1/\ln(L(\pi))$ smallest, $1/\ln(L(ka))$ smallest,
 $1/\ln(L(pr))$ smallest and $1/\ln(L(e))$ smallest.

Figure five to nine shows ionization plot for
 $P(\text{proton}) > 95\%$, $P(\text{proton}) > 80\%$,
 $P(\text{proton}) > 60\%$ and $P(\text{proton}) > 40\%$.

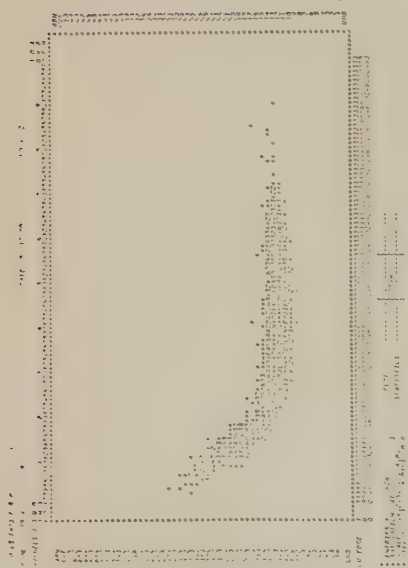


Figure 1

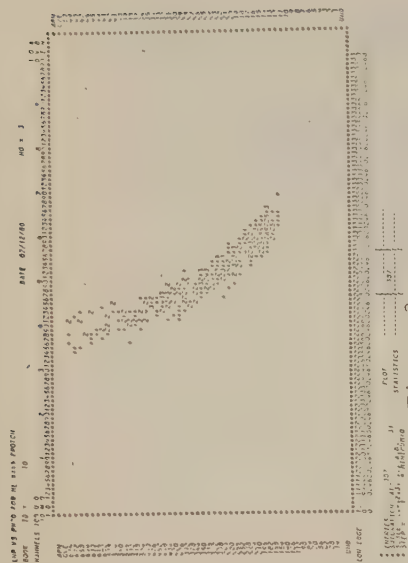


Figure 3

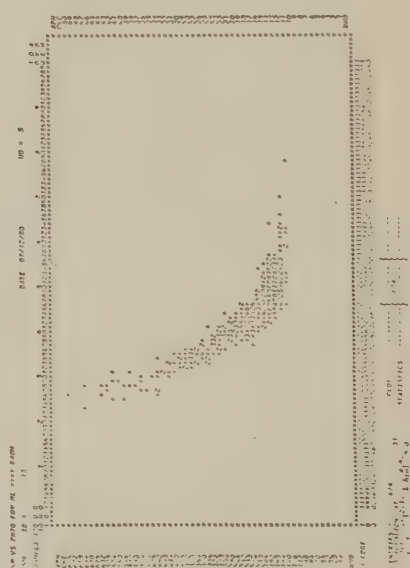


Figure 2

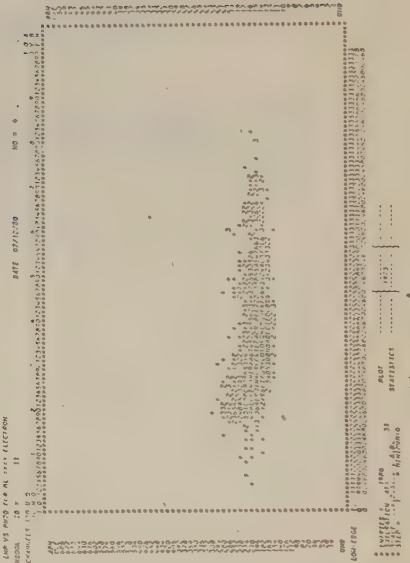


Figure 4

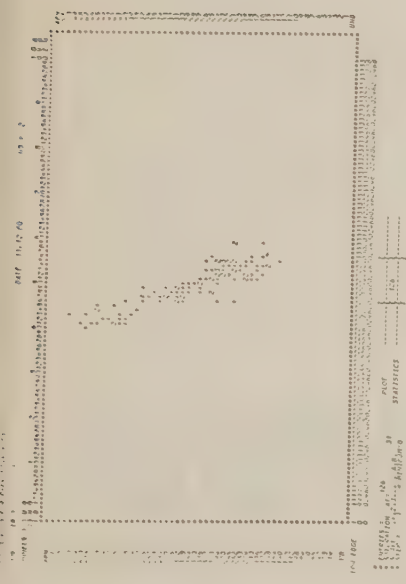


Figure 5

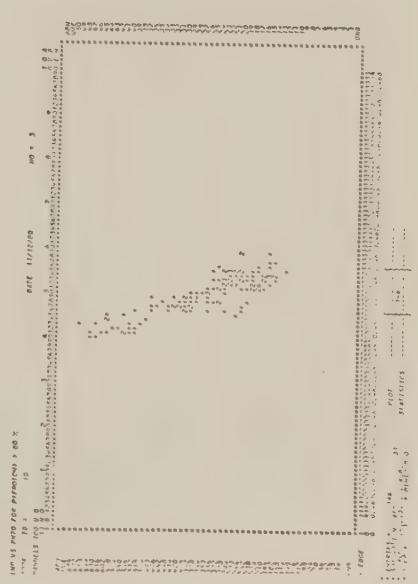


Figure 6

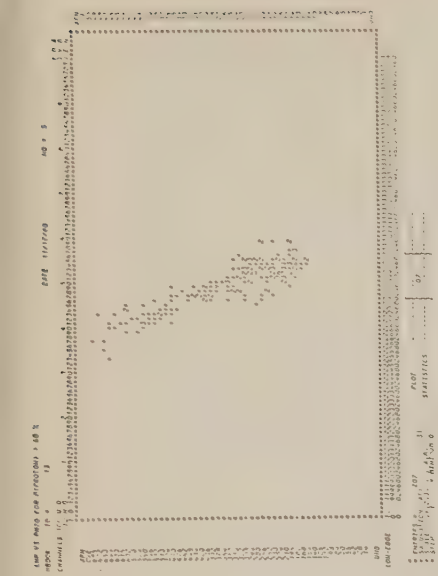


Figure 7

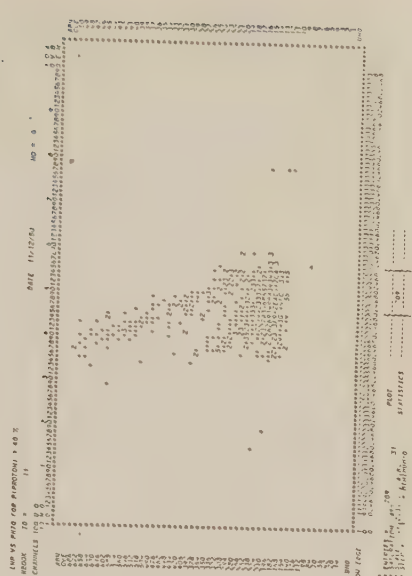
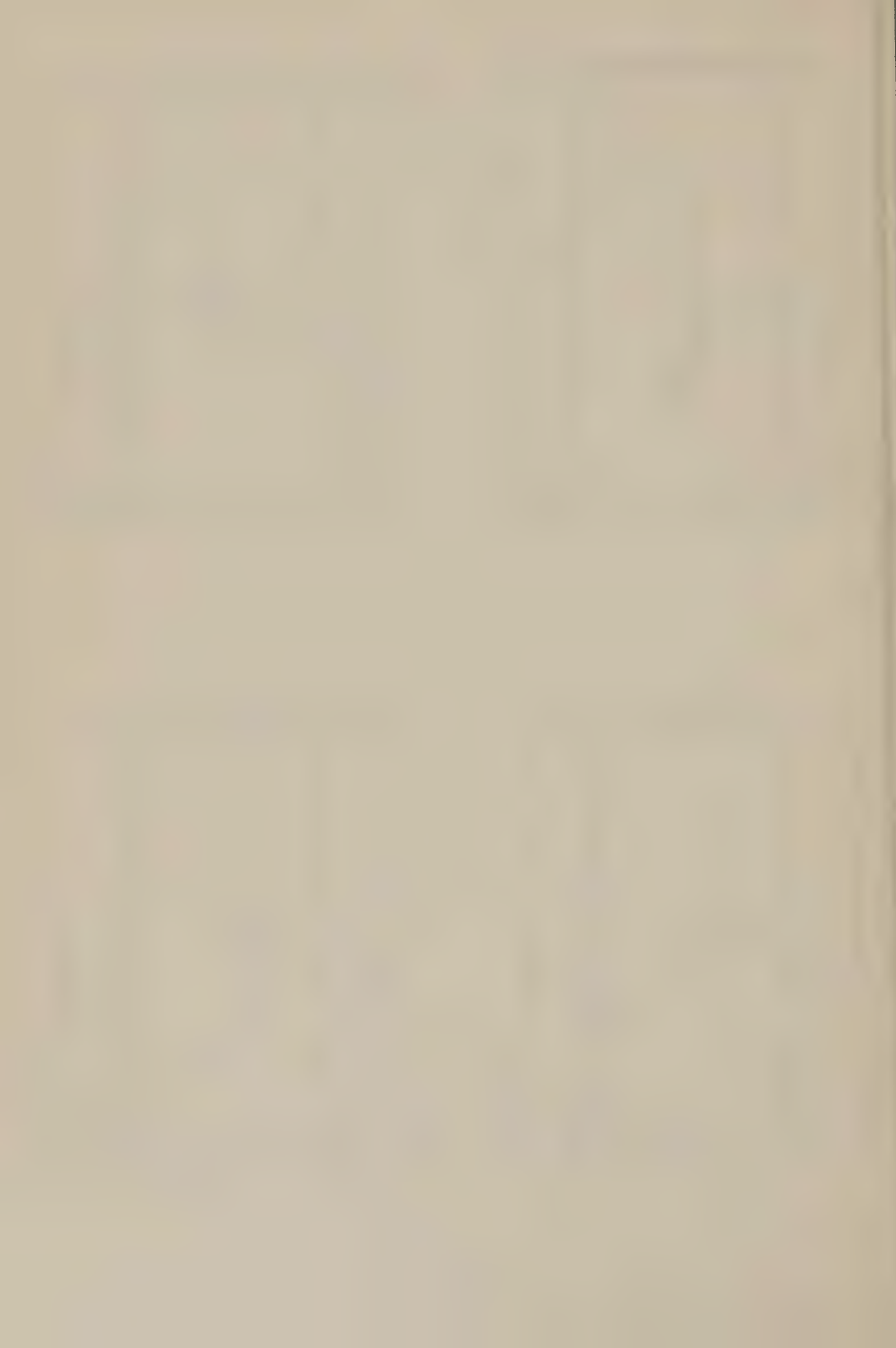


Figure 8



March 19, 1982

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Particle Identification with a Fine Sampling

Ionization Loss Detector

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PARTICLE IDENTIFICATION WITH A FINE SAMPLING

IONIZATION LOSS DETECTOR*

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Introduction

In a recent series of tests¹ it has been shown that the sensitivity for charged particle identification via the relativistic rise in ionization loss can be enhanced by using longitudinal drift and fast electronics to effect very small sampling intervals. With the chamber geometry illustrated in Fig. 1a (i.e., operation in the "time expansion" mode) electrons from individual ionizing collisions drift sequentially onto the anode wire with a time structure determined by the drift velocity in the gas. After fast pulse shaping the resultant waveform is digitized with a flash-encoding ADC at a frequency of 100MHz. For the tests described in Ref. 1 the smallest sampling interval was 1/4 mm, and the sensitivity of mass (velocity) discrimination was studied for 1 meter of track length with sampling intervals ranging from 1/4 mm/sample to 16 mm/sample, the upper end of this range being typical of conventional ionization sampling devices.

The results of these initial tests are summarized in Fig. 2 as a function of the sample size. The result achieved with 1 meter of conventional sampling (ISIS-1, Ref. 2) is shown for comparison. For large sample sizes the results are comparable to those of traditional techniques, and a significant improvement is achieved when the sampling frequency is increased by roughly an order of magnitude. These results were gotten with a small test chamber in which meter-long tracks were simulated by piecing together many traversals of a single drift gap. We report here on the status of further studies to see whether this improvement in sensitivity can be duplicated with a chamber of practical dimensions and many readout channels.

Test Configuration

For the present tests we use a multiplane chamber incorporating the geometry illustrated in Fig. 1b. Here the sense planes (anode plus field wires) are located symmetrically between planes of cathode wires with electrons drifting from either side. Each sense plane is instrumented with 10 active anode wires. The wire length is 20 cm and the anode wire diameter is 20 μ m. The chamber has 10 such planes (100 active wires) for a total depth along the beam of 40 cm. The test detector, which was constructed by the CERN EF Division, is shown in Fig. 4.

All tests have been carried out with a gas mixture of 80% argon/20% CO₂. The potentials on the cathode and field wires are adjusted to give a drift electric field of ~ 300 V/cm and an avalanche gain (for full α -N₂ supported by the U.S. Dept. of Energy.

charge collection) of $\sim 10^4$. The drift field was chosen to give an electron drift velocity of 1 cm/ μ sec, $\sim 1/5$ the saturated velocity in this gas mixture. The volume of uniform field (adequate for longitudinal drift measurements of dE/dx) extends to within ± 3 mm of the sense plane and ± 1 mm of the cathode planes. Hence, in principle, 80% of the track length through a chamber of this geometry is usable for ionization loss measurements.

The readout electronics chain is illustrated in Fig. 4. A low-noise, common-base preamplifier is attached directly to the end of each anode wire, followed by a shaping and filter amplifier which consists of a semi-Gaussian integrator with a pole-zero tail cancellation.³ The pulse width (FWHM) of the response to a single cluster of electrons (x-ray source) was set to be 20 nsec. For these tests the outputs of all preamplifiers in a given plane were summed as input to a single shaping amplifier. The shaped signal was digitized with a 6-bit (64 level) flash encoder operating at 100MHz. The digital output from each channel was buffered in a 6 x 256 bit shift register operating at the same clock speed,⁴ allowing the storage of ~ 2.5 μ sec of drift information in each channel. For the chamber configuration of Fig. 1a, and the chosen drift velocity, the total drift time is 1.8 μ sec and each 10 μ sec digitizing interval corresponds to .27 mm of track length.

The results reported here were obtained in a 3.5 GeV/c positive beam at the CERN Proton Synchrotron. Protons, pions and electrons were tagged with a pair of threshold Cerenkov counters and a lead glass shower counter. The beam was normally incident on the sense wire planes as indicated in Fig. 1.

Test Results

Figure 5 shows the ADC response for a single track crossing a drift cell. The first signal arrival at the anode wire occurs in bin 19, prior to which one sees a DC off-set level of ~ 13 counts which was provided in order to study the baseline behavior as the signal develops. Typical structure is observed, corresponding to the sequential arrival of clusters of drifting electrons. Individual clusters (i.e. the results of single ionizing collisions) are not resolved, but are blurred by the effects of electron diffusion, finite pulse shaping width, and the fact that the observed signal in a given time interval is a superposition of ionization loss from either side of the sense plane. At the beginning of the pulse train the signal is characteristically large, corresponding to the portion of track

(~ 3 mm) which lies in the high-field region near the sense wire plane. There the drift velocity is essentially saturated, and the collected charge per unit time is greater than that from the uniform drift region by a factor of about 5. For the illustrated track this initial pulse exceeds the dynamic range of the ADC.

Our procedure for evaluating the effectiveness of very fine sampling intervals for particle discrimination is to divide each track into sampling intervals of 2, 4, 16 or 64 of the rudimentary time bins. The charge is integrated in each interval, after subtracting the baseline, and the resultant samples used to evaluate a parametric estimator (e.g. the truncated mean) of the ionization loss for the track. By spreading the ionization charge over many measurements, each involving a small signal, the longitudinal drift technique is extremely sensitive to the stability of the baseline, and changes in the zero level during the charge collection time must be corrected for. Ideally, the signal processing electronics should obviate the need for such corrections. The tail-cancelling networks, for instance, are designed to remove one source of baseline shift. For the circuitry which we used in these tests another source, with similar effect, comes into play for collection times which are long compared to the single-electron shaping time: the cumulative effect of AC coupling in the system gave a time constant of ~ 10 μ sec, which is appreciable compared to the total drift time of ~ 2 μ sec. Hence the level of the baseline falls off during the course of the pulse train at a rate which is proportional to the signal charge. To the extent that the ADC data include a complete time history of the signal on the wire, this effect can be corrected for, on a track-by-track basis as illustrated in Fig. 5. Figure 6 shows the signal, for incident protons, averaged over many track segments. The shaded area indicates the contribution accounted for by the baseline correction, which is substantial. We stress that this off-line correction, which is necessary for the analysis of the present data, should not be necessary in principle and indeed is not consistent with the requirements of a practical detector. We are presently designing circuits which will incorporate dynamic baseline restoration in an effectively DC coupled amplifier chain.

In Fig. 7 we show pulse height distributions obtained from the data for electron and proton tracks, for both "large" and "small" sampling intervals. The 17 mm samples (Fig. 7a) were obtained by summing the digitized information over groups of 64 successive 10 nsec time bins. The 1/2 mm samples are similarly obtained, by summing in groups of 2. (Two successive digitizings span a time interval equal to the 20 nsec width of the shaping circuit's response to an impulse of charge.) The horizontal scales are in ADC counts, with 2 ADC counts corresponding roughly to the signal charge induced by a single drifting electron. The distributions in Fig. 7a are consistent with results obtained from conventional measurements of ionization loss in similar thicknesses of gas, except that the delta ray tail at large pulse heights is somewhat suppressed in our data by the limited dynamic range of the flash encoders. The small samples (Fig. 7b) exhibit a more pronounced dependence of the shape of the energy loss distribution on particle velocity: both the protons (minimum ionizing) and the electrons (on the Fermi plateau) have some contribution at zero pulse height, the electrons having a substantially broader spectrum. The relativistic rise, as measured, e.g. by the ratio of most probable energy loss for electrons and protons, is larger for the smaller sample size.

To compare the sensitivity for particle identification with previous results, we calculate the truncated mean pulse height for 1-meter track lengths. At the time of this test only 5 of the 10 planes in our chamber were fully instrumented with readout electronics, corresponding to ~ 20 cm of usable track length for

each incident particle. The useful track length was further restricted, by about a factor of two, by the requirement that the initial pulse from charge near the anode wire not exceed the range of the ADC. This was necessary for the baseline reconstruction discussed above. Hence, although one of the aims of this test was to investigate the performance of a device incorporating many of the characteristics of a full-scale detector, it was still necessary to assemble 1-meter track lengths from data accumulated over several successive particle traversals.

Having assembled an ensemble of 1-meter track lengths, each track was subdivided into various sampling intervals ranging from small (~ 2000 samples/meter) to large (~ 60 samples/meter) and the truncated mean, retaining the 40% smallest pulse heights, was calculated for each case. The results as a function of sample size, are shown in Fig. 8. The resolving power for distinguishing electrons and protons clearly improves as the sampling frequency is increased. The separation ($S_{99} = 3.6$) obtained with 17 mm sample size is comparable to that achieved with conventional dE/dx measurements over 1 meter of track length, as indicated by the point labeled ISIS-I on Fig. 2. The same set of tracks shows significantly better separation as the fine-sampling information is exploited. With the smallest sample size (1850 samples/meter of track) the figure of merit S_{99} is improved by a factor of ~ 2 over the conventional sampling geometry. The origin of this improved sensitivity is made visually clear in Fig. 8 (and is explored in detail in Ref. 1): the relativistic rise is enhanced at small sample sizes, with no degradation in rms width of the truncated mean distributions.

The values of S_{99} obtained in this test fall systematically below those of our previous measurements, which are summarized in Fig. 2. We may list several reasons contributing to the difference:

1. The present measurements involve a large chamber, with many readout channels. The previous tests employed a single readout channel.
2. Ionization charges drifting from either side of the symmetrically placed anode plane are simultaneously recorded in the present tests. This saves space, but must cost something in resolution.
3. Residual errors remain, for the present data, after the baseline correction discussed above. The previous tests involved much shorter drift times ($\lesssim 400$ ns), and no such corrections were required.

The first, and probably also the second, of these points are endemic to a large chamber of practical geometry utilizing this technique. We believe that errors associated with baseline stability can, with modified readout electronics, be reduced to the level at which no off-line correction is required.

Conclusions

In our earlier work¹ and in new results by other groups presented at this conference^{3,6} one has seen the potential for significantly improving the resolving power of relativistic rise measurements by exploiting longitudinal drift and fast digitizing electronics to achieve very fine sampling of the ionization loss. This opens the possibility of compact and uncomplicated structures for particle detectors covering large solid angles in colliding beam experiments. In the work presented here we have investigated the fine sampling technique in a chamber of many readout channels, incorporating electrode structures readily amenable to the construction of a large detector which optimizes the ratio of fiducial track length to total detector length. We conclude that, in terms of the separation parameter defined in Fig. 2, a discrimination power corresponding to $S_{99}(3.5 \text{ GeV/c}) \gtrsim 7$ is a realistic expectation for a

full scale detector of 1 meter fiducial length. This can be achieved with a detector whose total length is ≤ 1.5 m. A conventional device, with 1-2 cm samples, would require $\frac{1}{2}$ 3 m fiducial length to achieve the same sensitivity. (For the latter estimate we use the calculation of Allison & Cobb,² which has accurately predicted the performance of several large devices.)

We list here some of the issues which need further investigation before a full scale device can be feasibly undertaken:

- Stable control of the zero-signal level in the amplifier chain, as discussed above.
- Study of the response as a function of incident track angle; e.g. the sensitivity to local gain variations due to space charge effects.
- A systematic study of the momentum (velocity) dependence of the resolution.

In the meantime, a conceptual design for implementing such a detector in the environment of a high energy colliding beam experiment is given in Ref. 7.

Acknowledgments

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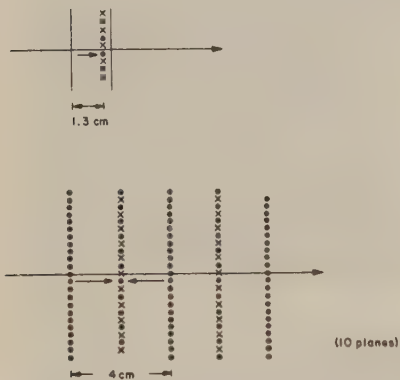


Fig. 1(a) Electrode geometry for the test chamber of Ref. 1. The long arrow represents a particle trajectory; the short arrow gives the direction of electron drift. The cathode planes are metal foils separated by 1.6 cm; (b) The geometry used for the tests reported here. The cathodes are wire planes. The full chamber consists of 10 active planes, of which 2 are shown here.

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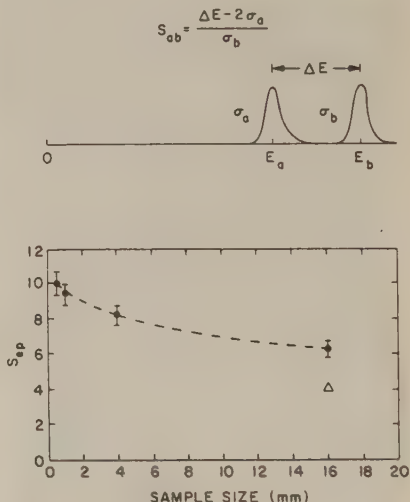


Fig. 2. The separation parameter S_{ab} is defined in the upper drawing, in terms of the difference ΔE between the centroids of the truncated mean distributions for particle types a and b, and the rms widths of the distributions. The lower plot summarizes the results from Ref. 1 for electrons and protons at 3.5 GeV/c, with 1 meter track lengths, as a function of the sample size. The open triangle gives the result from the ISIS-I detector (Ref. 2).

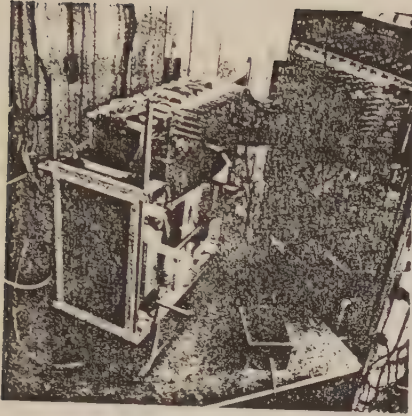


Fig. 3. The chamber just prior to insertion in the test beam. Direction of incidence is from the lower left. The wires are vertical, and the preamplifiers, seen at the top of the chamber, are attached directly to the ends of the anodes (there are 10 preamplifiers on each of 10 sense wire planes).

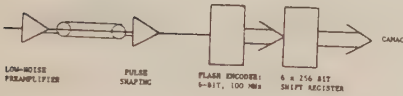


Fig. 4. The readout electronics chain.

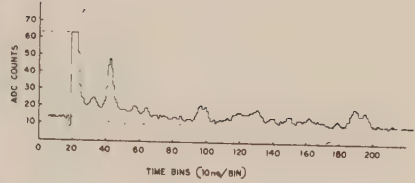


Fig. 5. The ADC response from a typical track through one cell (4 cm) of the chamber. Full range of the ADC is 64 counts on the vertical scale. The dotted curve under the signal gives the computed baseline for this event (see text).

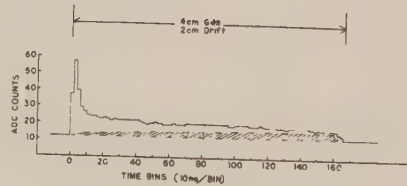


Fig. 6. The ADC response averaged over many (proton) tracks, after baseline correction. The shaded area falls below the baseline in the uncorrected data.

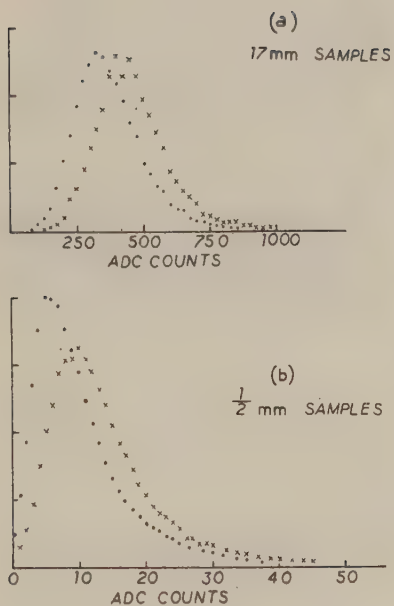


Fig. 7. Pulse height spectra for protons (dots) and electrons (x's). (a) 17 mm samples (64 time bins per sample); (b) $\frac{1}{2}$ mm samples (2 time bins per sample). Electrons and protons are normalized to the same area in each plot.

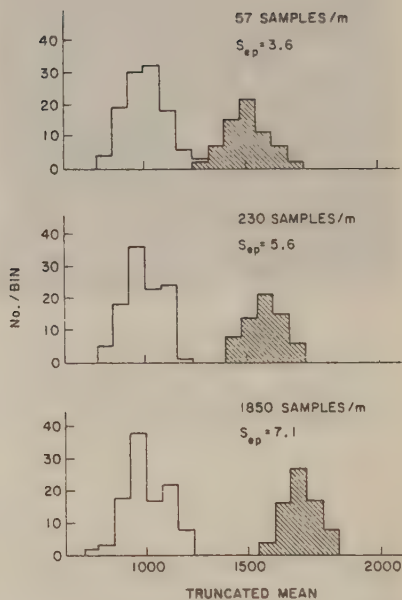


Fig. 8. The truncated means for 110 proton tracks (open histogram) and 72 electron tracks (shaded). Each track is 1 meter long. The results are shown for 3 different sample sizes.

